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In The Name of God

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ABSTRACT

Libya is a country of desert and the arid climate makes it in extreme lack of surface water. Groundwater then becomes a very important resource to meet the economical and agricultural demand in the northern coastal areas. Groundwater has been over-exploited and some problems occurred such as saline deterioration and aquifer deterioration since 1960s. To better understand these problems for a proper management solution, this project was setup for groundwater investigations aiming better management strategy in Wadi Baye as a case study based upon the governmental water management requirement.

Based on systematic literature review and data collection on geology, hydrogeology and other related environmental aspects, the groundwater systems were studied in terms of recharge and discharge, boundary and recharge and hydraulic characteristics using field based, hydrochemical/isotopic analysis and numerical modelling approaches. A series of techniques were employed to study the spatial and temporal variations of the groundwater flow field and hydrochemistry in the shallow and deep aquifer systems. The isotope signature was also used to understand the hydrochemical evolution of groundwater in Wadi Baye. It is found that the shallow groundwater is mainly influenced by the palaeo-saline hydro-environment, the deep groundwater geochemistry is impacted by mixture with the modern water around 50 km off the coastal line.

A 3D groundwater numerical model was built using ModFlow based on proper calculation and calibration of the major hydraulic parameters. Calculation of groundwater budgets shows that total annual averaged recharge is 167K m^3/d in Wadi Baye; the exploitable resources for shallow and deep aquifers are 33.7K and 15.6K m^3/d respectively. Groundwater exploitation potential indicates that both shallow and deep groundwater systems are under over-exploitation. Sensitivity analysis of hydraulic conductivity, specific yield (storitivity) and precipitation recharge shows that hydraulic conductivity poses the greatest impact to the model in Wadi Baye.

Three groundwater utilisation plans were proposed for further prediction in the future 10 years using the calibrated groundwater model. Modelling scenarios show that shallow and deep groundwater field will draw down under existing and increasing abstraction plans; drawdown in shallow groundwater will be greatly reduced if abstraction reduces to exploitable level and the overall flow field can remain stable or recover. However water level around the concentrated abstraction area will still drop down due to the localised negative balance by pumping. The best management strategy was proposed based on the modelling scenarios, to achieve a sustainable water management for the Wadi Baye area.

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Chapter 1 INTRODUCTION

1.1 Background

Arid regions have being featured with strong solar radiation, intensive evaporation, significant temperature variations and frequent sand storm, which result in vulnerable environment, particularly water environment due to the insufficiency and non-uniformity of precipitation. Therefore scientific and comprehensive insight into the water resources and environment in such a region is important for water sustainability. However, regional complexity and insufficient techniques and monitoring data always limited the study on water resources. Due to the rapid rise of the population and utilization of water resources, much more attention has been paid to water environment in recent decades. Long term monitoring and analyses of the hydrological processes and meteorological evolutions were performed, and serials of studies both in bench and lab scale were conducted to get better understanding of the water environment issues in arid region (Sen 2008), which benefited all relative researches.

A groundwater crisis with falling groundwater tables and contaminated aquifers has led to calls for urgent management responses. However, much of the discussion has been on the basis of anecdotal evidence (Brown and Halweil 1998; Postel 1999). There is a need to evaluate the hard evidence of there being such a crisis and to identify the types of management responses that actually works. Many countries and regional agencies maintain that these issues should be addressed within the specific contexts of the hydrogeological settings and the patterns of human use to which they are subjected. Proper recognition of the variability and characteristics of groundwater and aquifers, with effective management responses, is timely needed. So groundwater management for such a region is required to incorporate surface water (if available) and valuable groundwater resource.

Libya (see Figure 1.1) is a rapidly developing country with an oil-based economy and a potentially fertile coastal strip whose agricultural development has been inhibited by lack of adequate and reliable water resources. During the 1950s and 1960s oil exploration in the remote southern desert regions identified vast aquifers formed in the wet period corresponding to the European Ice Age. The exploitation of this water for desert-based irrigated agriculture projects was successful but limited by the reluctance of the coastal rural population to migrate to desert locations.

Groundwater serves as a reliable source of water for a variety of purposes in an arid country like Libya, including industrial and domestic uses and irrigation. The use of generally high-quality groundwater for irrigation dwarfs all other uses (Burke, 2002). Libya is located in the northeast of the Sahara Desert, see Figure 1.2, as the world's largest hot desert. At over 9,400,000 square kilometres, it covers most of Northern Africa, including Algeria, Chad, Egypt, Libya, Mali, Mauritania, Niger, and Sudan. The Sahara comprises several distinct eco-regions, and with their variations in temperature, rainfall, elevation, and soil, they possess distinct communities of plants and animals. The Sahara desert eco-region covers the hyper-arid central portion of the Sahara where rainfall is minimal and sporadic. Vegetation is rare, and this eco-region consists mostly of sand dunes (erg, chech, raoui), stone plateaus (hamadas), gravel plains (reg), dry valleys (wadis), and salt flats.

Figure 1.1   Location of Libya in the world (mapsofworld.com)

Most of the rivers and streams in the Sahara are seasonal or intermittent, the chief exception being the Nile River, which crosses the desert from its origins in central Africa to empty into the Mediterranean. Underground aquifers sometimes reach the surface, forming oases, including the Bahariya, Ghardaïa, Timimoun, and Siwah.

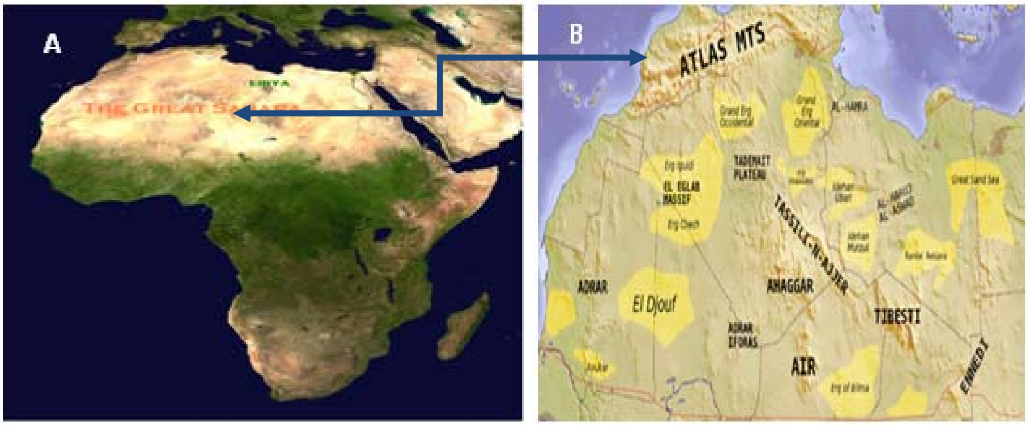

Figure 1.2 Geography of Africa showing the Saharan area (A), and the major topographic features (B) (NASA World Wind)

To the north of the Sahara reaches to the Mediterranean Sea in Libya, the Sahara borders Mediterranean forest, woodland, and scrub eco-regions of northern Africa, which has a Mediterranean climate characterised by a winter rainy season. The northern limit also corresponds to the 100 mm of annual precipitation. The climate has undergone enormous variation between wet and dry over the last few hundred thousand years.

The recognition that urban groundwater is a potentially valuable resource for potable, agriculture and industrial uses due to growing pressures on perceived less polluted rural groundwater has led to a requirement to assess the groundwater quality and contamination risk in urban areas from industrial contaminants such as chemical metals and nutrient. The development of a risk based management tool that predicts groundwater quality at potential new urban shallow and artisan wells are beneficial in determining the best sites for future resource development (Wang and

Yang 2008). According to the isotope methods for management of shared aquifers in Northern Africa, access to fresh water is one of the major issues of northern and sub-sub-Saharan Africa. The majority of the fresh water used for drinking and irrigation is obtained from large ground water basins where there is minor contemporary recharge and the aquifers cross national borders. The multiple isotope approach combining commonly used isotopes ^{18}O and ^{2}H together with more recently developed techniques (chlorofluorocarbons, ^{36}Cl, noble gases) can be applied to improve the conceptual model to study stratification and ground water flows (Kendall and McDonnell 1998). Moreover, the isotopes will be an important indicator of water quality changes in the aquifer due to water abstraction and saline intrusion, and therefore they will assist in the effort to establish a sustainable ground water management (Ma et al. 2007).

The northern Africa aquifer, the Nubian Sandstone Aquifer system (NSAS) is found in the Phanerozoic sedimentary sequences (sandstones, clays, and carbonates exceeding a thickness of 15 km) developed on the Arabian-Nubian Shield in Egypt, Libya, Chad and Sudan (Figure 1.3). It is one of the largest aquifers in the world, covering approximately a total of 2,000,000 km^2 of northeast Africa in an area dominated by desert and characterized by an arid to semiarid climate (Tait et al. 2004). And the Northwestern Sahara Basin extends over much of Algeria, Libya, and Tunisia and is today an arid region with rainfall mainly ranging from 20~100 mm/year (CEDARE 2001; Puri et al. 2001).

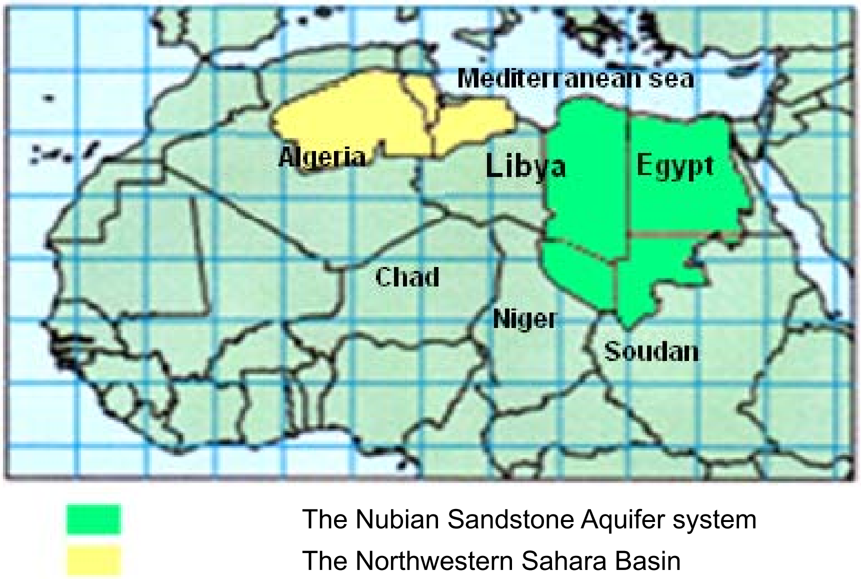

Figure 1.3 Shared groundwater basin

The southern part of Libya is a desert area of negligible population density overlying two of the largest groundwater basins: the Murzuk basin in the south-west and Kufra-Sarir basin in the south-east. Local use of these huge groundwater reserves is uneconomical due to poor soils and unsuitable climatic conditions. Extensive hydrogeological studies conducted during the last two decades indicated the possibility of transferring over 6 million m^3 per day to the coastal zones in the north. The Great Manmade River Project (GMRP) was launched in 1983 aiming at a rational utilisation of the transported water for agricultural and urban development, along with restoration of the affected aquifers. The project consists of five phases and is planned to be completed before the turn of the century. However it has been shown that some problems occurred during the water transfer, such as loss of water via evaporation, water pollution from land leaching, cost of maintenance and management. The related government, e.g. Ministry of Agriculture started to seek alternative groundwater supply in the northern coastal regions so that water can be supply will an ease of transport and management.

A scheme was proposed by the Department of Central Researches, Ministry Agriculture, Libya to develop localised groundwater supply systems in the northern regions along with Wadis Baye, Zamzam and Zakir. This was kicked off by an initial hydrogeological survey for potential groundwater quantity and quality so as to provide a sound source of water supply to the middle region. This project was based upon such a background, to carry out much further hydrogeological, hydrogeochemical, isotopic and numerical modelling study with a reasonable selection of a specific study area, the Wadi Baye catchment as a case study.

1.2 Aim and Objectives

The main aim of the study was to assess groundwater quantity and quality, by identify potential aquifer system in the Wadi Baye catchment as a case study area. Firstly, the hydrogeological field survey was planned based on the existing literature even proved to be very sparse. Further groundwater survey, sampling and analysis for quality and quantity of the objective aquifers were aimed to be undertaken. These would provide a sound foundation for detailed numerical modelling in the catchment for support of decision making for groundwater resource management. The specific objectives of the study are

1. To carry out thorough literature collection and collation using the area of Wadi Baye in the northern Libya;

2. To identify the potential aquifer systems in the Wadi Baye catchment so that further groundwater management can be undertaken;
3. To measure the groundwater head/level, collect water samples for geochemical and isotopic analysis;
4. To assess groundwater quality and quantity for the shallow and deep water systems with impact of saline intrusion and land use;
5. To construct a sound 3D groundwater numerical model, so that various management scenarios can be analysed;
6. To further understand the uncertainty of this modelling exercise and identify potential data need and areas for future study.

1.3 Research Tasks and Methodology

To achieve the above mentioned overall aim and objectives, the following major tasks were identified in this study:

1. The hydraulic characterisations of the aquifer and groundwater systems to be studied, leading to a reasonable hydrogeological conceptual model for numerical modelling based upon the field survey and desk study in Wadi Baye;
2. Detailed analyses of the temporal and spatial characterisation of the main geochemical species and hydro-geochemical evolution mechanisms with support of the hydrological and isotopic evidences;

3. A 3D numerical model for simulation of groundwater flow and advective transport in the study area, furthered with sensitivity/uncertainty analyses and groundwater management scenarios;
4. Proposals for exploitation and utilisation of groundwater resources in Wadi Baye for decision making, with support of groundwater quality evolution, modelling assessment and analytical calculations.

These tasks can be carried out with following research methodology by using a systematic approach for these staged hydrogeological studies, field work, laboratory analysis and numerical modelling, as shown in Figure 1.4. The following research framework has been followed in order to maintain a quality and smooth progress:

- Literatures collection and site conceptualisation, including geological, hydrogeological, meteorological and hydrological information;
- Borehole data analysis, aquifer system identification and geological model development with the GMS modelling tool;
- Hydrochemical data analysis using statistical calculations for insight into the spatial distribution of the hydrochemical characterizations;
- Multi-method data interpretation including mineral saturation index, ion proportion coefficient and isotopic evidence for hydrochemical evolution;
- Aquifer permeability determination from pumping test data, 3D numerical groundwater flow model with Visual MODFLOW;
- Assessment of groundwater resource and its exploitation potential based on groundwater budget analysis;

- Proposals for exploitation and utilisation of groundwater resource in Wadi Baye using analytical calculation and numerical modelling.

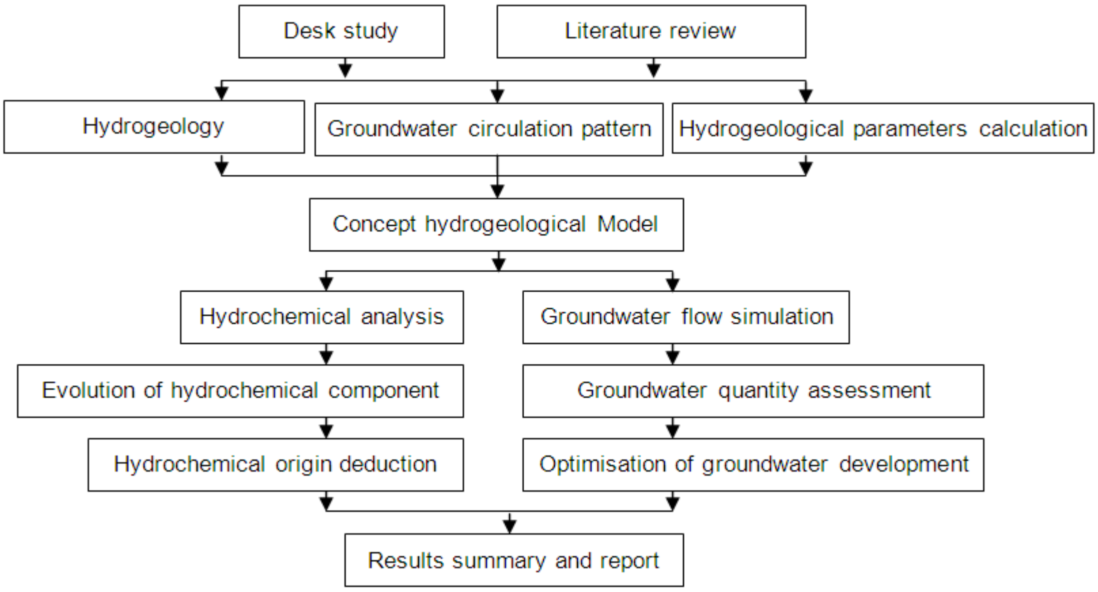

Figure 1.4 Flow chart showing the research framework

The conceptual model was setup based on author's literature review and desk study. The systematic research into hydrogeochemical, isotope and groundwater numerical modelling was a new challenge for this study area. A thorough effort was made toward understanding the groundwaterThe new findings will be useful for further water development and management in the Central Libya.

1.4 Thesis Structure and Organisation

The thesis is structured around the above specific objectives and tasks broken down into chapters. The order of the organisation reflects the transition of work shown in the research framework (Figure 1.4). More specifically each chapter addresses the following issues:

- **Chapter 1** illustrates the background of the study area and the issue, set up of the aim and objectives of the project, identification of major tasks and research methodology.
- **Chapter 2** is a brief literature review for groundwater management in arid region and Libya, application of groundwater modelling, isotopes and other issues around the work involved with this study.
- **Chapter 3** describes the general setting of the study area, Wadi Baye, in terms of geology, hydrogeology and groundwater system (shallow and deep).
- **Chapter 4** presents the field work and laboratory analysis work to support this project, from 2007-2010.
- **Chapter 5** details of water quality assessment and hydro-chemical evolution analysis with support of isotopes using the field monitored data.
- **Chapter 6** presents the comprehensive 3D groundwater numerical modelling with MODFLOW and further modelling scenarios.
- **Chapter 7** details further groundwater calculations for various groundwater resources in support management strategy.
- **Chapter 8** draws the conclusions of this study and show recommendations for potential study areas in the future.

Chapter 2 LITERATURE REVIEWS

2.1 Introduction

More than any other substance on the Earth, water is so important to life and has remarkable properties. On land water swirls and meanders through streams, falls from the sky, freezes into snow flakes, and finally goes into groundwater system and flows into the sea. It can however be completely different cycle in the arid regions, such Libya. Much water on the Earth's but just 3% of Earth's water is fresh water (Figure 2.1). Most freshwater is found as ice in the vast glaciers of Greenland and the immense ice sheets of Antarctica. That leaves just 0.6% of Earth's water that is freshwater that humans can easily use. Most liquid freshwater is found under the Earth's surface as groundwater, while the rest is found in lakes, rivers, and streams, and water vapour in the sky (Hoekstra, 2006).

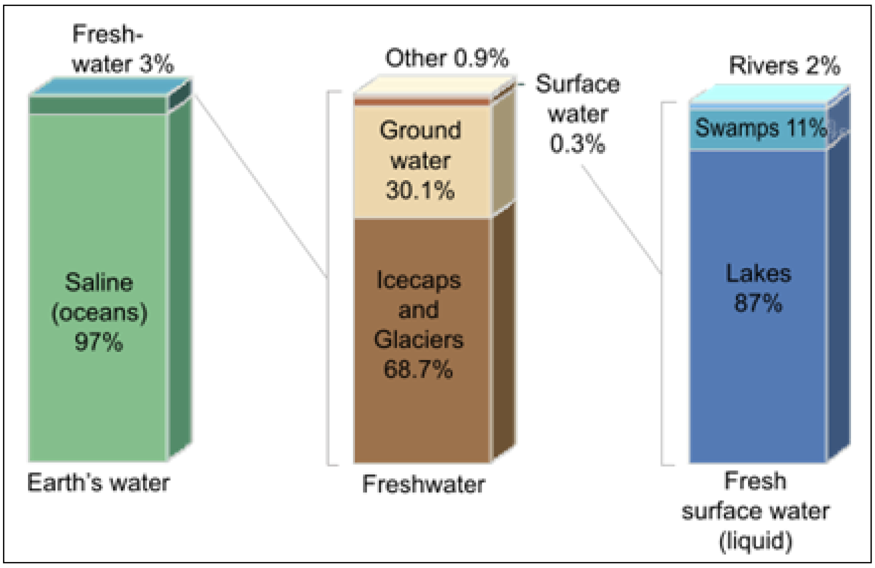

Figure 2.1 Distribution of water on the Earth (Web source)

Water is a special substance. It is abundant on Earth and frequently appears as a gas, liquid, and solid (three phases). Through the hydrological cycle, several compounds inform such as the evaporation, transpiration, rainfall and infiltration among above the ground surface and under the ground surface and the ocean; these can change the quality of water. Groundwater is also often withdrawn for agricultural, municipal and industrial use. Groundwater frequently interacts with surface water, Figure 2.2 is same examples of such (Younger 2006) but these can be completely different in semi-arid or arid countries.

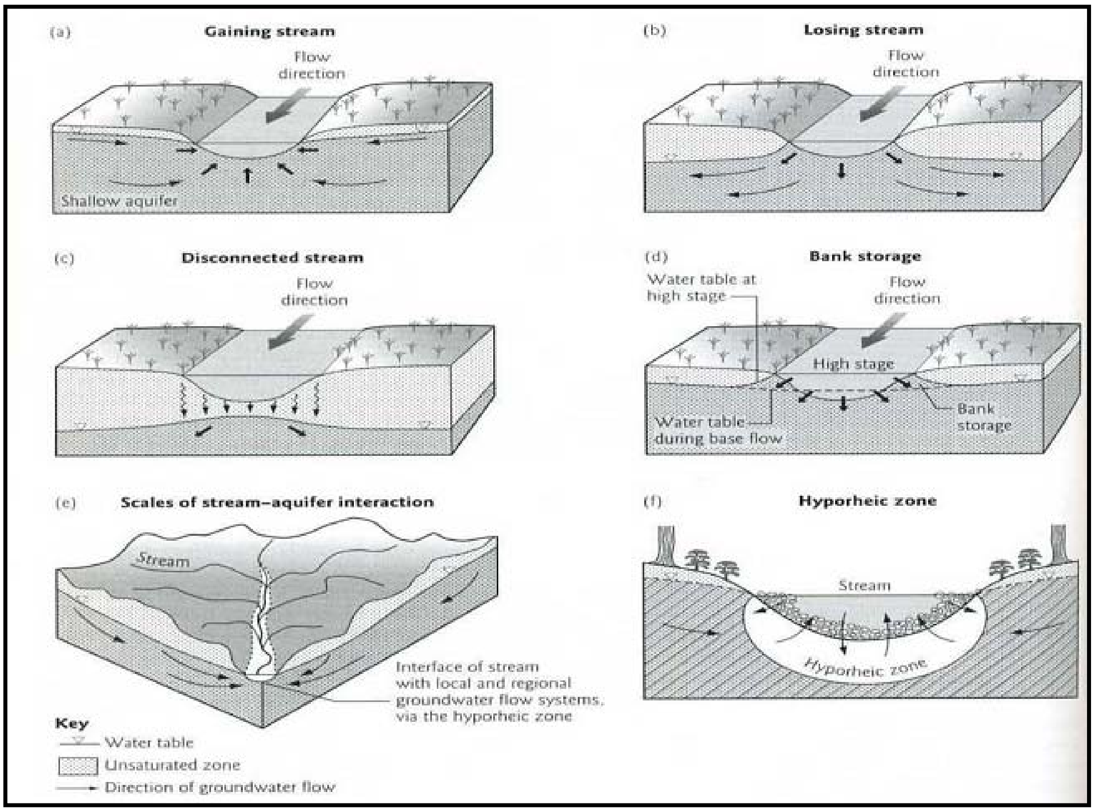

Figure 2.2 Relative groundwater travel times (Younger 2006)

2.2 Groundwater Management in Arid Regions

Water management is the activity of planning, developing, distributing and managing the optimum use of these limited water resources under defined water policies and regulations. Sustainable water management means to limit resource spending to a renewable or replaceable degree meanwhile profitability is closely related to the infrastructure management. An average of eighty per cent of the costs of any water management activity is originated by the infrastructure and independent from the transported volumes. Therefore the infrastructure management not only plays a key part for every water utility, it is also decisive for the overall efficiency of any water management policy (Fry et al. 2008).

One third of the world's land surface is classified as arid or semi-arid. In most of the world easily developed land is already exploited, and therefore increasing attention is turning to arid areas to relieve population pressures and to provide more food. Soil and water natural resources of arid and semi-arid regions are often in a delicate environmental balance. Arid regions cannot be developed along lines that have been successful in humid areas. These regions are under severe and increasing water stress due to expanding populations, increasing per capita water use, and limited water resources. The world's total population has increased four times in the past 150 years and may double again in the next 30 years. Future projections indicate that by 2025, five billion people will live in countries experiencing moderate or severe water stress (WHO 1997; Arnell 1999). Evidently, conditions will be most severe for the driest regions of the world. Effective management is essential, and this requires appropriate understanding of the hydrological processes in arid and semiarid areas (Wheather and Al-Weshah 2002).

Climatologic, morphologic, and geologic conditions that affect the hydrological phenomena are different from each other. For instance, in humid and tropical regions abundance of rainfall and consequent runoff and snowmelt provides time and spatial distributions that are more convenient than arid or semi-arid regions, where they are rather haphazard and sporadic. With more pressure on water resources, the natural occurrence, distribution, and movement of water become more sensitive and, accordingly, hydrologic principles should be followed more carefully for better planning, operation, maintenance, and management of water resources, especially in arid and semi-arid regions.

According to Pilgrim et al. (1988) and UNESCO classification (UNESCO 1977), nearly half of the countries in the world face aridity problems. There is an obvious need for an improved understanding of arid and semi-arid regional hydrology and hydrogeology, and for the development of appropriate techniques in hydrologic modeling. Although some aspects of arid zone hydrology are more amenable to simplified modeling, it is highly probable that greater errors and uncertainty will continue to characterize results for arid zones. Recognition of these problems is fundamental to realistic approaches in arid zone modeling, rational interpretation, and applications.

The majority of countries in arid and semi-arid regions depend either on groundwater or on desalinization for their water supply, both of which enable them to use water in amounts far exceeding the estimated renewable fresh water in the Wetlands can retain water, especially during dry (non-rainy) periods, and thus can enhance recharge to major aquifers. However, in arid and semi-arid areas, where groundwater recharge occurs after flood events, changes in the frequency and magnitude of rainfall events will alter the number of recharge events. The term Wadi Hydrology recently, in order to distinguish between humid and arid region methodologies, was coined for arid region water resources exploitation and management. It is our purpose of this PhD project to present particular research into the arid region assessment methodologies from different aspects of water resources.

2.2.1 Arid region classification

All hydro-activities are dependent on climate and therefore it is useful to classify arid and humid regions according to the context of interest. Meteorologically they are classified on the basis of temperature and precipitation as showed in Figure 2.3 (Zen 2008).

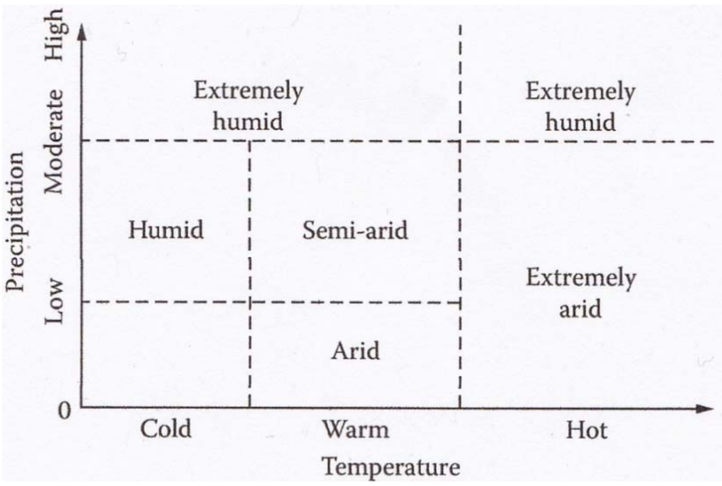

Figure 2.3 Classification of aridity and humidity

Almost one third of the world lies in the arid zone and it can be very warm or cold. Arid regions are defined as having a dry climate with little or no rainfall, very low humidity, and a high annual evaporation rate that exceeds the annual rainfall, with a high deficit in soil humidity that does not give way to even dry farming practices. On the other hand, the scarce and sporadic rainfall is turbulent, brief, and torrential. The nature of this rainfall causes an increase in runoff, erosion, and flooding, which furnishes conditions that must be taken into consideration by water resources planners and operators in selecting a site for human activities or configuration for a settlement center (Zen 2008).

Geographically, most arid and semi-arid regions occur between 10° and 35° latitude (e.g., Sahara and Kalahari deserts), in the interior parts of continents (Australia, Gobi desert) and in rain shadow areas in fold belts (Peru, Nepal). Large parts of the arctic tundra receive less than 250 mm precipitation per annum and qualify as “semi-arid regions,” too. In practice, each person or different researchers may have different meaning for aridity and humidity. Arid and semi-arid regions are also distinguished on the basis of their annual rainfall sums and the following categories can be identified: 1) deserts where the annual total rainfall sum is less than 50 mm/year and devoid of vegetation; 2) arid regions where the annual total rainfall sum is between 50 mm/year and 250 mm/year with sparse vegetation; 3) semi-arid regions where the annual total rainfall sum varies between 250 mm/year to 500 mm/year coupled with steppe vegetation (Krol et al. 2006). Deserts are primarily hot because of their lack of water. Desert is cold at night because of water lacking in the ground, and there is little water vapor in the air.

In addition to severe water scarcity in arid regions, water resources in wadi hydrologic systems are characterized by significant spatial and temporal variability. In general, assessment and management are the key factors in any integrated development strategy for water resources. Without a correct and detailed assessment, it is almost impossible to plan, design, realize, and manage any water resources development project. The results of the assessment and subsequent management are the bases for any decision-making process, as they can lead to large investments and serious consequences to the environment. Proper management and utilization of wadi flow depend essentially on the availability of the data, as well as analysis techniques (Mugabe et al. 2007; Zen 2008).

Unfortunately, in many arid and semi-arid countries water resources data are not always available, which has negative effects on the development process. Water resources assessment consists of determining their quantity, quality, and variability for sustainable development and rational management (Dickhoefer et al. 2010).

2.2.2 Safe yield and groundwater management

Groundwater management deals with the complex interaction between human societal activities and the physical environment, which poses an extremely complex and difficult problem to solve for the benefit of all parties involved.

The safe yield of an aquifer was defined 1920s as the water that can be abstracted permanently from an aquifer without producing any undesirable results. Todd also defined the perennial yield as the flow of water that can be abstracted from a given aquifer without producing results that lead to an adverse situation (Younger 2006). Each aquifer will have a different safe yield, depending on the way it is exploited, on changes in natural recharge due to land-use modifications, and on the introduction of engineered changes in recharge, such as different forms of artificial recharge. The key point in each of these definitions is the consensus on the "undesirable" or "adverse" results. In arid regions such as Libya, the deeper the well, the more the groundwater potentiality, which causes friction between rich and poor people.

All the above mentioned points are from the quantity point of view; however, the groundwater quality is more of a concern in many cases than the quantity. The groundwater quality variations are more difficult to control, manage, and solve, and they are not well perceived and understood by various people (Ma et al. 2007; Singh 2010). Once an aquifer is depleted, especially in arid regions, it will take generations to recover. The issue is not conservation for conservation's sake, but maintaining a vital resource for use in perpetuity. Strategic planning does not mean either aquifer overexploitation or storage of groundwater more than necessary (Kannel et al. 2008).

2.2.3 Groundwater for needs in arid regions

Water resources management can be a set of actions to be realized for medium and long-term planning. These actions have to consider all recommendations and measures resulting from the planning process. Water resources management is a daily or monthly task that has to be carried out with the participation of all parties related to the water sector. Quantitative and qualitative aspects must be taken into consideration as, equitable distribution of water according to the allocation plan; rational and efficient use of water; protection of water quality and aquatic ecosystems; and management of exceptional phenomena, such as drought, floods, etc. (Zen 2008; Singh 2010).

Groundwater reservoirs are the most abundant and dependable freshwater sources in many parts of the world. Their mineralogical composition makes the taste and chemical composition very suitable for various human activities including domestic, agricultural, and industrial uses. It is almost the only water source in arid and semi-arid regions, but it is not available in desired quantities temporally and spatially. Sporadic, rare, and haphazard rainfall occurrences cause rather unpredictable natural groundwater recharge possibilities. It is, therefore, necessary to lay down the strategic groundwater reservoir assessment basic variables and their subsequent scientific and technical processing for future development and management (Younger 2006; Singh 2010). The general features in any groundwater future planning should include the following points: 1) spatial and temporal environment; 2) hydrogeology and hydrochemistry; 3) alternative strategies; 4) emergency situations.

Warnings of the shortage of water resources and environmental pollution, especially in arid region, have led to calls for urgent groundwater management and environmental protection responses. Many researchers have done much study on the development and management of groundwater, for example, Jha (2009) discussed the methods of artificial recharge of groundwater to improve the efficiency of artificial recharge. However, an accurate estimate of the groundwater recharge and the parameter acquisition in specific sites are major concern in groundwater management. Libya is a typical country in arid region which is facing the challenge of solving the problem of shortage of water resources. The world has moved on since then with many of the social and imperatives outweighing a considered, balanced approach to groundwater development and management. More recent approaches (World Bank, 1998, 1999) have developed the sustainable management principles.

The time lags inherent in the dynamic response of groundwater to development have generally been ignored by water management agencies, decades after scientific understanding of the issue was consolidated. In brief, the effects of groundwater overdraft (although undeniably real) may take decades or centuries to manifest themselves (Sophocleous 2002) modelled a situation where groundwater extraction in an intermountain basin withdrew the entire annual recharge, leaving 'nothing' for the natural groundwater-dependent vegetation community. Even when the bore field was situated close to the vegetation, 30% of the original vegetation demand could still be met by the lag inherent in the system after 100 years. By year 500 this had reduced to 0%, signalling complete death of the groundwater-dependent vegetation. The science has been available to make these calculations for decades; however water management agencies have generally ignored effects which will appear outside the rough timeframe of political elections (3 to 5 years) (Scott et al. 2007).

In arid and semi-arid zones groundwater plays a key role in all forms of development and it is extracted, in many countries, by deep mining of fossil water. In Libya and Saudi Arabia, for example, massive water mining schemes were developed in the 1980s and 1990s. In the Arabian Peninsula abstraction from deep aquifers has caused an alarming depletion of non-renewable groundwater aquifers but in urban areas there are equally alarming increases in the level of contaminated groundwater because of leakage from water and wastewater networks and excess irrigation. UNESCO and other international bodies recognizes the importance of groundwater as a vital natural resource. Groundwater was a key component in the International Hydrological Programme (IHP: 1975 to date). In the Fifth Phase of IHP (1996-2001) groundwater was adopted as the principal priority of the programme, playing a prominent role in at least two of its eight themes: “Groundwater Resources at Risk” and “Integrated Water Resources Management in Arid and Semi-Arid Zones”. This focus continues in the current phase of the IHP (2002-2007), which contains initiatives related to shared aquifers (ISARM), a centre for Global Groundwater Assessment (IGRAC), developing isotope hydrology techniques (JIIHP), management of groundwater in arid and semi arid zones (G-WADI), regional networks on Wadi Hydrology and Groundwater Protection in the Arab region, regional centres for training water resources management in arid and semi arid zones in Egypt and Chili, and an International Centre for Qanats and Historic Hydraulic Structures in the city of Yazd in Iran. Besides, methods of heat dynamics computation and isotope were introduced by Rouabhia et al to explore the groundwater chemical evolution and the supply sources in an arid area (Scanlon et al. 2006).

Mexico counts with 4,000 dams and other hydraulic infrastructure with a storage capacity of 180 cubic kilometres, which account for 44% of the annual flow. In the arid regions, dams are mostly used for irrigation. In the humid areas, dams are mostly used for electricity generation and flood protection in Mexico (Aquastat 2008).

Namibia is a semi arid country on the south west coast of Africa. It has some large man-made dams which are primary spots for fishing. Largemouth bass fishing is popular in Namibia due to breeding programs of this alien species indigenous to North America, and many dams have aided their population with the import of this species.

The qanat technology is known to have developed in pre-Islamic Iran which has the oldest and longest Qanat (older than 3000 years and longer than 71 km) (Mays 2010) and then spread to other cultures. Instances include a recently discovered falaj system in al-Ain, UAE, which dates to 1000 BC, and another in Umm Safah, Sharja, which dates to the Iron Age. Also, a qanat-like system called the Turpan water system originated in China during the Han Dynasty (206 BCE – 24 CE) (Turpan 2010).

The value of a qanat is directly related to the quality, volume and regularity of the water flow. Much of the population of Iran and other arid countries in Asia and North Africa historically depended upon the water from qantat; the areas of population corresponded closely to the areas where qantat are possible (Masoud 1991; Michel 2001).

2.2.4 Groundwater Recharge in Arid Region

Groundwater recharge is a hydraulic process where water is routed to the subsurface and specific aquifer is recharged by runoff from external environment. When the groundwater recharge is more than the withdrawal, the groundwater storage in aquifer will get positive equilibrium. Conversely, negative equilibrium will be notable if the withdrawal excesses the recharge, and the groundwater resources may be exhausted.

Therefore, accurately assessment of the groundwater recharge is critical in groundwater evolution and also is important to the resources utilization. Since the 1900s, consendation water and native water were regard as two main source of the groundwater recharge in arid region. Especially, the theory “ condensation water” indicates that scarce precipitation is consumed by the intensie evaporation in arid region, so that the rainfall does not recharge the aquifer and contribute to the groundwater storage. Kazakhstan hydrogeologists found that most aquifers in arid region were recharged from the humid mountain area by rainfall and infiltration, which implicated the mistake of consendation water and native water theory (Li, 1995). Lloyd (1990) pointed out that the main groundwater recharge involved rainfall and infiltration in mountain area, runoff recharge in surface water body and bays, and the retaining water process. Ultimately, all mentioned above were from precipitation. However, the precipitation was scarce in the centre of hinterland and infiltration recharge decreased sharply. Therefore, lateral runoff became the primary recharge source of regional groundwater.

The main methods of calculation of groundwater recharge include: hydro-geo-chemical method, physical method and numerical method, all of which will be described as follow.

1) Hydro-geo-chemical methods

Hydro-geo-chemical method is a developing approach to assess the groundwater recharge in recent decades. It attracted much attention and especially was employed in arid regional study, such as the tracing method. Several primary tracers include ^{36}Cl, ^{2}H, ^{3}H and ^{18}O (Edson, 1998). Cl was used to quantify the rate of groundwater recharge firstly at 1969 by Eriksson (1969). Then mass balance and profile method of Cl were put forward by Eriksson and Allison (Eriksson, 1976; Allison, 1978). Consequently, tracing method using Cl was employed widely for the study of groundwater recharge in arid/semi-arid region. E.Zagana (2007) calculated the groundwater recharge of 3 different aquifers in arid/semi-arid region in Jordan using Cl^- mass balance method. A.M.Subyani (2004) estimated the rate of groundwater recharge in Wadi Tharad in Saudi Arabia, which located in arid/semi-arid region, and the study pointed out that only 11% of the precipitation recharged the aquifer. Heilweil (2004) calculated the groundwater recharge based on the profile analyses of Cl^- and the rate was up to 0.5~13mm/a, which may indicated that there was preferential flow in groundwater compared with the present value 3~60mm/a (Heilweil etc. 2006).

Isotope technique was popular increasingly recent decades, and many hydrologists employed this method to assess the groundwater recharge in arid/semi-arid/semi-arid region. Two main isotope methods include isotopic mass blance and isotope peak displacement method (Mebus, 2005). Zimmermann (1967) studied the recharge and evaporation of groundwater based on the isotope peak displacement of 3H in soil, and the same method was used to find out that the recharge was up to 23mm in Dahna in Saudi Arabia. Liu (1997) studied the isotopic signatures of the shallow groundwater, river and rainfall, and then pointed out that the river recharged the groundwater. The age and recharge rate of groundwater were also calculated by an exponential model of 3H.

2) Physical methods

Physical method includes lysimeter testing method, zero flux profile method and dynamic variation analysis of groundwater. Lysimeter testing method can get the recharge rate of groundwater directly and accurately. It also was used to verify the recharge rate calculated by other methods, however, the construction and operation usually were very complicated and cost too much. Especially, the result just can represent a point value and can not reflect the spatial variability. Therefore, lysimeter testing method usually was employed at a specific small site.

Zero flux profile (ZFP) means a profile where the gradient of hydraulic head in soil is zero and water is routed to the groundwater system. ZFP is the boundary that soil water move up or down, while the later indicates groundwater is recharged (Wellings etc. 1982). ZFP was put forward firstly by Richards etc (1956). They analyzed the soil water flux and deduced the soil unsaturated ratio based on the soil moisture and water potential. Sharma (1991) assessed the recharge rate in western Austrillia using ZFP method, and the rate was near to 34 -49 mm. Lei (1988) put forward a modified positioning flux profile method to calculate the infiltration rate and evaporation of the soilwater successfully, which was also discussed by Zhou etc. (1998) to estimate the infiltration rate in hinterland.

Dynamic variation analysis of groundwater couples the groundwater table with the groundwater storage of the aquifer, featuring a high sensitivity in arid region. This method is regarded as the most cost-effective and promising method. Goes (1999) calculated the recharge of monsoon flood to the aquifer in arid region in northern Nigeria based upon the analysis of dynamic variation of groundwater.

3) Numerical methods

Numerical method is performed to calculate the groundwater recharge by numerical modeling. Due to the development of the computer technique, numerical modeling has being driven to resolve the accurate calculation of groundwater recharge with high precision. Several main numerical models include bucket model, HELP, HYDRUS, ESTEL, EARTH, SWMS and VS2DT (Yang and Wang 2010).

Admittedly, all methods for assessment of groundwater recharge feature with uncertainty, temporal-spatial scale, and limited applicability. Therefore, co-operation and verification with each other are important when these methods are introduced to resolve practical problem, so that accurate and reliable results can be obtained.

2.3 Research into Groundwater Management

At the beginning of the 21st century, concern exists worldwide for human sustenance on an Earth where finite water and land resources must be shared by humans and the environment. It is widely recognized that groundwater is a vital source of freshwater for communities around the world, and that this fragile natural resource is vulnerable to over-exploitation and chemical contamination, and constrained by climatic variability. Nations around the world are confronted with the difficult task of sustainable groundwater management (Morris et al 2003; Planning Commission This task is beset with challenges of science and technology, as well as of human behaviour. There is much debate among scientists, social workers, policy makers and legislators on optimal groundwater management approaches (Reilly et al 2008; Yang and Wang 2010).

During the 16th and 17th centuries, the conceptual foundations of modern groundwater hydrology were laid when Palissy, Perrault and Marriot in France observationally established that natural flows in springs and base-flow in perennial rivers were fed by rainfall (Narasimhan 2005). Early during the nineteenth century, these ideas came together, providing a rational approach to drilling deep artesian wells in the Paris Basin.

2.3.1 Water development and driving forces

In the past three decades, the water resources in Libya had a high priority in its development. This was necessary to meet the water requirements of the ever increasing population growth, and the huge demands from agricultural, domestic, and industrial sectors. The country has experienced a severe depletion and pollution as a result of water resources unavailability, which appears clearly in several populated locations at the coastal strip. Continuing the present pattern of using these resources causes more strain on its availability and has a major affect on social, economic, and environmental life. Considering the country's economic situation, its huge area, the climate conditions, and the scattered population in so many areas all over the country, an immediate need of better water resources policy is necessary to maintain an acceptable living standard and to ensure a secure life for the future generations

(Abufayed and Committee 1999; Abufayed 2001)

This avenue of water management shall be considered in this study, with emphasis on allocation management, the institutional and regulatory steps that are increasingly important rather than the numerical assessment of the resource or its use (Otchet 2000). In addition to overdraft, groundwater systems are particularly vulnerable to chemical contamination. Once contaminated, it is extremely difficult, if not impossible, to decontaminate them. The second half of the twentieth century has witnessed documentation of chemical contamination in shallow as well as deep groundwater systems due to various human activities such as seepage from landfills, agriculture, dairy farms, mine wastes, industrial effluents and septic tanks in rural areas (Morris et al 2003). Contamination from heavy metals and organic chemicals used as pesticides pose special public health concerns because these contaminants can be toxic even in such small quantities as parts per billion (Scheidleder et al 1999).

The European Water Framework Directive (2000/60/EC) is an example of recent efforts. A main advantage of the explicit linkage of legislation and management to the basin level is of the Directive leads to difficulties, especially in transboundry basins – between countries or administrative regions of a country – where institutional coordination is required responsible for planning, management and control of water resources at the basin level system and integrate the stakeholders in the decision process. However, the implementation the opportunity to address directly the needs and problems of the natural hydrological to develop coherent water management legislation, promote creation of institutions (Yang and Wang 2010).

Drought management needs to be integrated into the long-term strategies for water management incorporating improved early warning and monitoring systems (Wilhite 2005). The development of specific drought contingency plans is at early stage in most countries. Example of detailed and operational plan is provided by the urban water supplier CYII that manages water for the metropolitan area of Madrid (Cubillo et al. 2003). The plan is based on the comprehensive understanding of the demands of the system, the strategic reserves of the stored volume and the level of guarantee for the water supply. It is surprising that international initiatives such as The United Nations Convention to Combat Desertification (UNCCD 2002) that provides the global framework for implementing drought mitigation strategies, and the United Nations International Strategy for Disaster Reduction (UNISDR 2002) that establishes a protocol for drought risk analysis, have not been taken into account for the preparation of the local drought management plans. Water saving is a key strategy for overall reduction of societal vulnerability to drought. Water reuse and desalinization technologies at market rates and wide scale are recent but are developing fast, with significant efficiency gains, placing the cost at about 0.22 €/m3 and 0.48 €/m3 for brackish and sea waters, respectively (Garrido and Iglesias 2006). Irrigation technology is increasing water and land productivity with outstanding savings and benefits to ecosystems (Garrido and Iglesias 2006). The adoption of water saving measures requires education and participation of the users.

Real public participation in water management is difficult to quantify, since participation in all countries is mainly theoretical. The data presented in the table is based in a comparative evaluation of the institutional analysis performed with a common methodology. It is difficult to compare results with other individual studies. For example Barreira (2003) carefully analysed the implications of the EU WFD for the Iberian peninsula, concluding low public participation, but does not provide a scale to compare with other Mediterranean countries. The level of participation reflects the proportion of stakeholders legally represented in water management bodies in each country.

The ownership of surface and groundwater results to complications for the application of legislation and other aspects of water management. Common aspects of the region is the public ownership of surface water and the partially private ownership of groundwater, as well as the intensive groundwater use without restrictions or legal rights. Groundwater reserves have been and continue to be the largest buffer in water scarcity situations, but a large range of negative effects has been documented for its overuse (Llamas and Martinez-Santos 2005).

Global examples include the developments in India, Pakistan, Yemen, Eritrea, and Egypt, among others (Custodio and Llamas 2001; Moench et al. 2003) compile tens of studies in, which the role of groundwater is highlighted and its social importance emphasised. However, groundwater pumping should be controlled because excessive use of the aquifers can cause overexploitation problems with the consequent negative environmental, social and economic impact. The main challenge to sustainable groundwater is to maintain its social and strategic value (Garrido and Iglesias 2006). In most cases, almost all groundwater abstracted is used for irrigation, groundwater provides a significant part of irrigation water to the farm sector in Algeria, Morocco, Egypt, Turkey and Tunisia (Fornes et al. 2005). Spain and Italy rely heavily on groundwater as well. Conjunctive use of surface-groundwater resources has been around for decades. For example, the urban supply system of Madrid and more than 100 of municipalities (pop. 5.5 mill) depends on groundwater to face scarcity situations of moderate to severe level (Cubillo and Ibanez 2003). Technology for desalination, reuse and use of brackish waters has evolved significantly in recent years (Calatrava and Sayadi 2005; Bazzani et al. 2005; Saadi and Ouazzani 2004) and many users in the Mediterranean region can today use these waters at affordable prices (Garrido and Iglesias 2006). However the alternative of desalinized water as a massive supply, for example in agriculture it is still non-sustainable. This section describes a framework for risk management of water scarcity based on the analysis of the current adaptation strategies to water scarcity in Mediterranean countries that provides a systematic approach to prevent and/or minimize the impacts of drought on people. The framework is developed in the context of current drought vulnerability, management, and technologies (see previous section) and intends to be broad enough to incorporate new criteria for establishing priorities as societies change or as scientific and technological aspects of drought management improve. The framework includes the following components.

The mathematical or numerical models are usually based on the real physics the groundwater flow systems. These mathematical equations are solved using numerical codes such as Modflow, FeFlow, HydroGeoSphere, Gwflow and US

Geological Survey Water Resources Ground Water Software etc. Various types of numerical solutions like the finite difference method and the finite element method are discussed in the article on h. The model may have chemical components like water salinity, soil salinity and other quality indicators of water and soil, for which inputs may also be needed.

Monitoring and early warning of potential water quality and quantity is a key component of the water management plan (Wilhite 1996; Wilhite 2005). Continuous improvements of technology in instrumental monitoring devices (i.e., gauges, piezometers, etc) play a key role for accounting of resources. Drought indices adequately calibrated represent local features of the water resources system of the basin they can be used as auxiliary tools for drought monitoring and forecasting (Wilhite 2005). Realistic models appropriate for water management need to be incorporated in monitoring and early warning system (Rossi et al. 2003; Cancelliere et al. 2006). The scientific advances in understanding variations of the climate system offer an opportunity to develop prediction methods.

Finally economic instruments contribute to the design of effective management but alone are ineffective. Water markets, tariffication, and reallocation of rights with financial compensation, may be adequate in some cases (Garrido et al. 2005). Groundwater resources play a vital role in meeting water demands, not only as regards quality and quantity, but also in space and time, and are of vital importance for alleviating the effects of drought (Llamas et al. 2005; Garrido et al.2006). Although groundwater has been used historically, the technology to use groundwater intensively has been developed in the last 50 years, and used intensively in arid and semi-arid countries to satisfy the demands for water supply and irrigation. The pressure on groundwater resources in the last decades partially arises from the intensive development of intensive irrigated agricultural areas.

2.3.2 Exploitation & utilization of groundwater in arid region

More than a half of global counties have been affected by arid climate, most of which take groundwater as the primary source of water supply. Therefore, the sustainable exploitation & utilization of groundwater is critical for the regional development. Especially, reasonable exploitation model has become a hotspot, which depends on scientific deployment and allocation according to the temporal-spatial distribution of water resources, and it is the basic approach to maintain social & political development and eco-environmental protection. Therefore, to determine the most reasonable exploitation model of groundwater becomes the most critical issue (Sun, 2002). In the western USA, agricultural irrigation resulted in over-exploitation of the groundwater, dry-up of the rivers and contaminations. Subsequently, a comprehensive exploitation & utilization plan was formulated to realize the unified deployment of the groundwater quality and quantity. Dufresne (1999) performed the water resources appraisal in Florida by MODFLOW and predicted the influence of the groundwater withdrawal to surrounding environment. In addition, the study pointed out that combined utilization of surface water and spring should be conducted as reasonable exploitation & utilization model.

To sum up, groundwater resource is so important that reasonable exploitation

& utilization plan should be put forward as the guarantee for sustainable development. Simulations based on numerical modelling and combined deployment of surface water and groundwater become the most promising approaches to optimize the water exploitation & utilization. It must be noted that the plan also depends on the specific conditions of the study area. For example, environmental issues related to exploitation activities should not be ignored, such as soil salinisation and ecological water demand. In brief, many present studies on hydro-geology in arid/semi-arid region were conducted, however, to make reasonable plan for groundwater exploitation & utilization will still be hotspot, and much more attention should be pay for prevention of the eco-environmental deterioration.

2.3.3 Impact of climate change

Climate change projections for the region derived from global climate model driven by socio-economic scenarios result in an increase of temperature (1.5 to 3.6°C in the 2050s) and precipitation decreases in most of the territory (about 10 to 20% decreases, depending on the season in the 2050s) (IPCC 2001). Climate change projections also indicate an increased likelihood of droughts (Kerr 2005) and variability of precipitation – in time, space, and intensity – that would directly influence water resources availability. The combination of long-term change (e.g., warmer average temperatures) and greater extremes (e.g., droughts) can have decisive impacts on water demand, with further impact on the ecosystems. Under all climate change scenarios in the Mediterranean region, available water resources decrease while irrigation demand increases (El-Shaer et al. 1997; Iglesias et al. 2006). Under current conditions all Mediterranean countries also face significant problems due to the unbalanced distribution of water resources, conflicts among users, and between 780 countries and it seems most likely that climate change will lead to an intensification of these problems. The effects of sea level rise in North Africa, especially on the coast of the Delta region of Egypt, would impose additional constraints to the use of resources (IPCC 2001). If climate change results in intensification of drought, available water resources in the Mediterranean region may become increasingly unstable and vulnerable. Drought management in both regulated and unregulated systems will have to adapt to the slow evolution of climate. The human dimension of climate change in the Mediterranean may not stop at the country' boundaries, since there is the potential for more pronounced water conflicts with neighbouring regions (i.e., transboundary issues in the Nile and in many shared aquifers).

The management of the decreasing water resources, as a result of the climatic changes within the Mediterranean region, is challenged in particular, as climate change coincides with high development pressures, increasing populations, and high agricultural demands. Evidence for limited capacity to cope with socio-economic and agricultural demands in the Mediterranean region can be documented in recent history. For example, water reserves were not able to cope with extensive droughts in the late 1990s in Spain, Morocco and Tunisia, causing many irrigation dependent agricultural systems to cease production (Goderniaux et al. 2009).

Effective measures to cope with long-term drought and water scarcity are limited and difficult to implement due to the variety of stakeholders involved and the lack of adequate means to negotiate new policies. The distribution of aridity observed at any one point in time is largely the result of the general circulation of the The latter does change significantly over time through climate change. In addition, changes in land use can result in greater demands on soil water and induce a higher degree of aridity (Jyrkama and Sykes 2007).

2.3.4 Sea water intrusion

Usually there is a contact zone between the sea water and fresh water due to the difference of their density in subsurface aquifer in coastal zone. The abrupt interface model and the seawater-freshwater transition zone model are two main models in contact zone. The abrupt interface model thinks that there is an abrupt interface between seawater and freshwater, and they are immiscible. The seawater-freshwater transition zone model insists that they are not immiscible and a transition zone with a gradient of density exists in this zone. Both the two models have their respective practicability, especially the former usually was applied while the transition zone was narrow or the intrusion was slight due to the "immiscible" condition. Actually, the dispersion and diffusion in transition zone could not be ignored. Ghyben and Herzberg in 1901 firstly studied the abrupt interface and their study indicated that the distance based on a series of assumptions (Werner and Simmons 2009).

Hubbert (1940) determined the position of the interface by mathematic calculation based on the observation of water head, and then induced the Hubbert formation. However, the interface could not de determined exactly so that it limited the application of the formation. Lzuka estimated the interface by the analysis of the hydraulic gradient variation during drilling. Zhou (2008) also used the hydraulic head difference between the freshwater zone and the sea water zone to determine the interface.

Henry put forward the homogeneous fluid transition zone model, and determined the analytical resolution to the concentration in vertical profile that orthogonal to coastline under confined steady flow condition. Henry also pointed out the ocean circulation. Pinder obtained the numerical resolution to Henry's model and then verified it (Abd-Elhamida and Javadi 2011).

In brief, the abrupt interface model and the seawater-freshwater transition zone model were introduced to study the seawater intrusion. The analytical method features simply resolution process and easily to understand. Numerical model can be used to simulate the influence of multi-variance such as the hydro-geological conditions and groundwater withdrawal, for this reason, numerical model is much more popular.

2.4 Groundwater Study in Libya

2.4.1 Groundwater resources

In 1953, the search for new oilfields in the deserts of southern Libya led to the discovery not only of the significant oil reserves, but also vast quantities of fresh water trapped in the underlying strata. The majority of this water was collected between 38,000 and14,000 years ago, though some pockets are only 7,000 years old.

There are four major underground basins. The Kufra basin, lying in the south east, near the Egyptian border, covers an area of 350,000 km^2, forming an aquifer layer over 2,000 m deep, with an estimated capacity of 20,000 km^3 in the Libyan sector. The 600m-deep aquifer in the Sirt basin is estimated to hold over 10,000 km^3 of water, while the 450,000 km^2 Murzuk basin, south of Jabal Fezzan, is estimated to hold 4,800 km^3. Further water lies in the Hamadah and Jufrah basins, which extend from the Qargaf Arch and Jabal Sawda to the coast Figure 2.4. These vast reserves offer almost unlimited amounts of water for the Libyan people, these basins consist of several aquifers which deferent in terms of geology ages and aquifers characteristics (water technology, GMRP Project in Libya).

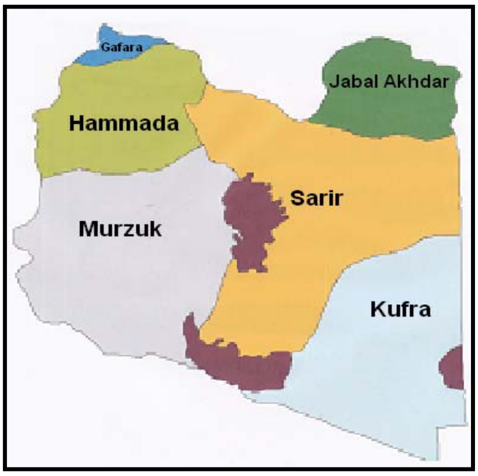

Figure 2.4 Groundwater basin Libya (source: General Water Authority, Libya)

In Libya 90% of its area is covered by desert. Owning to the little rainfall and surface water, groundwater becomes a unique important water supply in all aspects of life. On the other hand, the development of economy is unbalanced in Libya. 80% of Libya's inhabitants, nearly 4.7 million, resident in the coastal area, and 8% of the country's agriculture production comes from the coastal plains. Therefore, Water consumption is increasing as a result of the agricultural development in coastal plains.

The problems associated with over exploitation of groundwater are the decline of groundwater level, seawater intrusion and so on. The supply and demand of water resources stayed balanced in 1950s, with annual water consumption of 30 million cubic meters. Then the groundwater level began to decline by the late 1950s, but it did not cause seawater intrusion until 1980s as the groundwater was exploited more severely and the aquifer was damaged. Luckily, a huge aquifer was discovered during the oil exploration in the Libyan desert in 1960s. Then, the government initiated the “Great Manmade River” project of transferring the groundwater from the desert region in the south and the coastal region in order to utilize the groundwater in desert to support economic development in coastal area. By now, 3 of the total 5 stages of this project have been finished. Besides, the government encourages public and private researches on the investigation and evaluation of water resources and environment in northern area, which will provide a basis for solving these environmental and geological problems and supply more water resources Figure 2.5.

Figure 2.5 Tadrart Acacus desert in western Libya, part of the Sahara

Groundwater availability and quality are however, vulnerable both to climate change and over-abstraction. In Libyan cities where the water table has lowered there has been a consequent impact on agricultural activities. Groundwater aquifers are either renewable or non-renewable. The renewable aquifers are those located in the north coastal strip with high precipitation rates. The large non-renewable sedimentary groundwater basins cover extensive areas in the central and southern parts of Libya and contribute large quantities of freshwater for local use, industrial and agricultural development. Seawater intrusion is a problem in the coastal areas of Libya. Most productive agricultural fields are in the northern coastal areas of the country where irrigation predominantly relies on groundwater. Seawater has moved inland because of heavy exploitation of the Miocene-Quaternary aquifer in order to meet the increasing water demand. The physical and chemical parameters of groundwater such as electrical conductivity, pH, temperature and individual ion content were determined. Most of the wells showed high values of electrical conductivity. The increase of water salinity is directly related to the extreme pumping of shallow coastal aquifers and movement of seawater towards inland. In some samples the increase of salinity corresponds to the ions abundant in seawater. In those solutions molar ratios of Cl/Br indicate influence of seawater intrusion.

2.4.2 Groundwater management in Libya

Libya is located in the northeast part of the Sahara, and 90% of the land is desert and semi-desert area, which features typical continental arid/semi-arid climate. There is no perennial river in Libya, and nearly all country depends on groundwater for its water supplies (Iglesias etc. 2007). In addition, the exploitation and utilization of water resources displays spatial non-uniformity, because almost 80% of the population inhabit in cities in northern coast plain, such as the capital Tripoli, and 80% of the agriculture productivity are developed in coast plain. Extensive groundwater exploitation has been developing in northern coast plain from 1950s because of increasing water demand. Actually, the groundwater withdraw has exceeded the minable quantity in this region, and the excessive groundwater depletion resulted in the decline of groundwater hydraulic head and then formed depression cone in specific area, in addition, the dewatering of aquifers, sea water intrusion and saline-saline-alkali soil amelioration become serious environmental problems (Rajab, 1995). For example, good equilibrium between water supply and demand was kept in Jifarah plain at 1950s, with a water depletion of 30 million m^3 a year. However, groundwater table had been descending since 1960s due to the increasing water demand, and the groundwater in this region was highly over-exploited at 1980s, the reduction of groundwater storage was near to 140 billion m^3, which leaded to serious sea water intrusion and the salty - freshwater interface moved into inland with the distance of 1~2km. In addition, the salinity of groundwater increased sharply from 150 to 1000 mg/L (Dong, 1988). Therefore, the groundwater resources in coast plain in Libya have being challenged by both water quantity and quality.

Large amounts of fresh water were found during the petroleum exploitation in southern Libya at 1960s. Considerable groundwater can be withdrawn from the subsurface aquifer and then release the water supply-demand pressure. The famous

"Great Manmade River Project" was conducted at 1983 to transfer the water resources in southern Libya to the northern part. The project was divided into 5 phases in 30 years, and 3 phases have been finished so far. However, the huge investment, difficulties in techniques and long construction period hamper the operation & maintenance of this project. Consequently, the government performed studies on water resources issues in northern Libya, which actually conducted series of investigations and assessments in northern developed region where the industry and agriculture are prosperous.

Admittedly, few studies have been conducted and hydrological researches are in the initial stage in Libya. That is to say, few present researches can be used as references. Therefore, a comprehensive study was conducted in Wadi Baye in northern Libya. Based on detailed investigations and analyses of geological and hydrogeological conditions, the quality and quantity of groundwater were assessed, and the genesis of regional groundwater environment also was studied. Then the planning and utilization of groundwater were promoted, and reasonable exploitation amount and scheme were determined to keep stable groundwater table. All works above will be helpful to the control and management of groundwater contamination, prevent the geo-environmental hazardous and protect the safety of water supply.

Given the importance of groundwater in Libya as the main supply source it's essential to cover the large deficit in the water in various activities agricultural, industrial and drinking water. On this basic the Libyan state has taken several decisions to protect and benefit from the groundwater. Including the establishment of institutions and scientific organizations and the expansion of researches and studies of how to develop and manage water and process update technology. And for this foundation was the one of the goals the transfer of water from the desert to cities coastal and farming plains, this is GMRP.

The climatic studies, in general, and rainfall studies in particular, are new products in Libya because there were few meteorological stations before 1969 and even the ones that existed were working in a narrow scope. Due to the huge area (1,755,500 km^2) of the country with 90% of deserts, it is difficult, if not impossible, to cover all this area by sufficient meteorology stations. All the above reasons contributed to shortages and drawbacks in the meteorological studies. As a result, any attempt to study the meteorological variables that exist over Libya, is expected to have a significant probability of error. On the other hand, the study area, which lies in the northern parts, contains the Gefara plain in the west corner of the country (11100 km^2) and the Al-Jabal Al-Akhdar mountainous area in the eastern corner.

These are the most important agricultural locations and majority of the Libya's population is concentrated along the Mediterranean coast. This region is influenced mainly by the Mediterranean sea climate as mild winters and not excessively hot but dry summers with high humidity and substantial rainfall. Most of the 750-800 BCM per annum of global groundwater withdrawals are used for irrigation of agricultural crops (Shah et aI, 2000). During the last two decades, there has been a significant increase in the use of groundwater for irrigation particularly in India, the USA, China, Pakistan, Iran and Mexico which are reported as the largest consumers of groundwater

80 Qanats a Unique Groundwater Management Tool in Arid Regions: The Case of Bam Region in Iran (Poste 1999). In these countries, farmers are pumping groundwater faster than its natural replenishment rate, causing a continuous drop in groundwater tables and depletion of the resource.

2.4.3 Great Man-made River Project

The Great Man-made River Project (GMRP) is a network of pipes that supplies water to the Sahara Desert in Libya, from the Nubian Sandstone Aquifer System fossil aquifer. It is the world's largest irrigation project. It is the largest underground network of pipes and aqueducts in the world. It consists of more than 1,300 wells, most more than 500 m deep, and supplies 6,500,000 m^3 of fresh water per day to the cities of Tripoli, Benghazi, Sirt and elsewhere CEDRE 2001. The project was divided into five Phases as the following:

Phase I, as the first and largest phase, providing 2 million m^3/day along a 1,200 km pipeline from As-Sarir and Tazerbo to Benghazi and Sirt, via the Ajdabiya reservoir, was formally inaugurated in August 1991. This was a massive undertaking, using a quarter of a million sections of concrete pipe, 2.5 million t of cement, 13 million ton of aggregate, 2 million km of pre-stressed wire and requiring 85 million m^3 of excavation, for a finished cost of $14 billion.

Phase II delivers 1 million m^3/day from the Fezzan region to the fertile Jeffara plain in the western coastal belt and also supplies Tripoli. The system starts at a wellfield at Sarir Qattusah, consisting of 127 wells distributed along three east-west collector pipelines and ultimately feeds a 28 million m^3 terminal reservoir at Suq El

Ahad.

Phase III falls into two main parts. Firstly, it will provide the planned expansion of the existing Phase I system, adding an additional 1.68 million m^3/day along with 700km of new pipeline and new pumping stations to produce a final total capacity to 3.68 million m^3/day. Secondly, it will supply 138,000m^3/day to Tobruk and the coast from a new well field at Al Jaghboub. This will require the construction of a reservoir south of Tobruk and the laying of a further 500 Km of pipeline.

The preliminary engineering and design contract runs for 41 months and includes geotechnical and topographic surveys. The conceptual designs phase features extensive consideration of pipeline routing and profiling, hydraulics, pumping stations, M&E, control/ communications system, reservoirs and other structures, corrosion control, power, operational support and maintenance provision. The evaluation of tenders for the detailed design is expected in the first quarter of 2005.

The last two phases of the project involve the extension of the distribution network together with the construction of a pipeline linking the Ajdabiya reservoir to Tobruk and finally the connection at Sirt of the eastern and western systems into a single network.

When completed, irrigation water from the GMRP will enable about 155,000 ha of land to be cultivated.

Artesian groundwater levels have fallen dramatically due to pumping. A major consideration of these strategies is the Great Man Made River project as shown in Figure 2.6. The initial intention is to utilise the artesian groundwater available from a number of wells close by the project. It is proposed at some point in the near future to to supply the project from the GMRP Phase III pipeline. The total irrigation layout for for the given project area can only be irrigated once a reliable and large enough supply form the GMRP is obtained, in the meantime the limited supply from the four wells can be used to initiate the development of the irrigated agriculture Salem et al.1997, 2002.

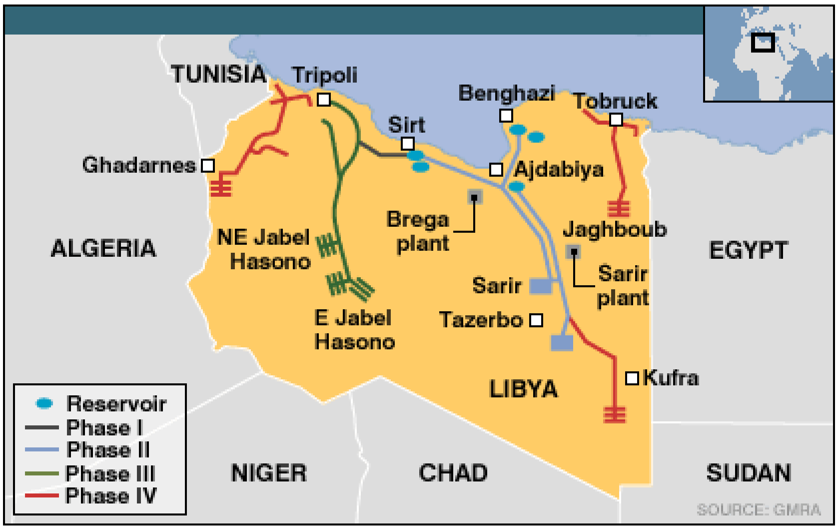

Figure 2.6 Great Man-made river scheme (Source: Libya Water Grid, LWG)

The alignment of the GMRP Phase III pipeline passes close to the northern boundary of the project area. The pipeline will link Phase I to the east and Phase II to the west to help balance supply and demand within the network. The design capacity of the link pipe is 0.98 Million cubic metres per day (11.3 m^3/s).

It is understood that sufficient irrigation water from GMRP Phase III will be available for the proposed development at Wadi Baye. The earliest date for availability of GMRP water is not known but for the purposes of this analysis it has been assumed to be after five years. The details of the water supply that will be made available are not known, consequently it has been assumed that some long term storage will be required, the size and location of which will be determined at a later date

Water from GMRP Phase III will be conveyed to the site by a branch pipeline, feeding the storage reservoir. It has been assumed that these works will be constructed under a separate contract, possibly as part of a greater Wadi Baye project to develop other potential arable areas to the south. It has also been assumed that the branch would be aligned along the road that forms the northern project boundary and that there will be sufficient pressure available from the system to command the three proposed buffer reservoirs without the need for additional pumping. There is no provision in the Wadi Baye Al Kabir Project as a case study for the construction of the branch pipeline to the site, the storage reservoir, or any booster pump stations. See Figure 2.7 illustrating the stages of groundwater development in Wadi Baye. We must continue to research, how to solve the water problems after wards.

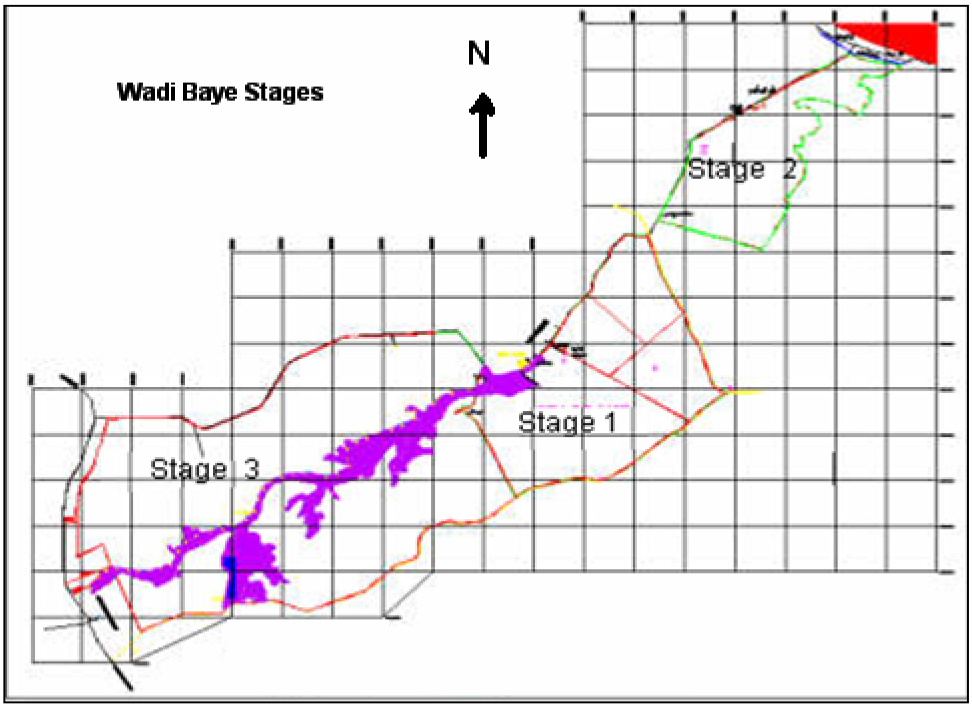

Figure 2.7 The stages groundwater development in Wadi Baye

Calculations for a variety of crops were made for irrigation using the groundwater and GMRP water. For design purposes a leaching factor of 10% has been adopted, this provides a conservative estimate for when GMRP water is in use and covers most cropping eventualities when groundwater is in use. In addition to the water use efficiency, the corresponding reduction or leaching factors have been applied to the volumetric monthly irrigation water requirement for each crop to give the corresponding gross IWR.

2.4.4 Groundwater management in Wadi Baye as a case study

In Libya there is a growing awareness of increasing demand for fresh water while main supply is limited. This situation of water supply has become more problematic with rapidly increasing population and low rainfall. Aiming an understanding the environmental problems with over-exploration of shallow groundwater in arid area, the Libya government applies the groundwater management for all area with groundwater especially in central and south area in the country. For this reason Agriculture and Water Ministries made decision to develop a part of the Wadi Baye area and consent to develop 2200 ha from the total area 81000 ha in the first stage in Wadi Baye, which is a background of this project.

The only water resource in Wadi Baye is groundwater. Groundwater production has been from naturally overflowing wells – rainfall has been very seldom and the rate is nearly 50 mm per year, usually runoff in Wadi Baye event each 25 to 30 years. The weather temperature has been 40˚C in the summer and decrease on the other seasons.

In current stage groundwater in Wadi Baye area is used for agriculture purposes. An controlled irrigation system designed by Halcrow has been used to water 600 ha crops (barley, wheat, corn, Rhodes grass and alfalfa) with full time and 1600 ha part time for grass rural purpose (Halcrow 2001); it is used in the rest areas for breeding camels and sheep, goats, wildlife animals (e.g. wild deer) and Ostrich farms. Development for any other future purposes is undergoing. Figure 2.8 presents some pictures of various water uses.

Figure 2.8 Some water uses for the Stage 1 in Wadi Baye

As it is mentioned before that precipitation is virtually zero in this area and thus the contribution from rainfall to plant growth can been simply ignored. On every irrigation system there are water losses; the ratio between the water used by the plant and the amount supplied known as ‘irrigation efficiency’ can be low. The irrigation of desert soils increases the risk of salinisation, particularly if the drainage is partially impeded and the irrigation water is moderately saline. In order to ensure that potentially harmful salts are not deposited in the root zone, additional water is applied to leach the salts (Abufayed and Committee 1999).

The irrigation system is operated via irrigation network that was installing with deep wells, pipelines and eight cooling ponds and two reservoirs. See Figure 2.8 for the design map. The chosen method of cooling of the groundwater is ponds; no mechanical cooling aids are envisaged. This approach is relatively easy to operate and has been chosen mainly as a result of local preference for a technically simple, easy to operate and maintain.

Two cooling ponds in series have been used at each well. The first (hot) pond reduces the water temperature from 73° C to 51° C. The second (cool) pond reduces from 51° C to 40°C. The cooling ponds were designed for the flow rate specific to each well and to achieve the levels of cooling in the hottest month (August). Actual cooling levels achieved in hot and cool ponds will increase with decreased flow into the ponds or with cooler ambient conditions. The inlet and outlet pipes are directly opposite each other to ensure the hot water does not short circuit the cooling effect provided by the volume and surface area of water in the pond.

The water discharges into each pond at the surface and is drawn-off at the floor level. The flow into and out of the ponds should not result in any turbulence or significant approach velocities to ensure maximum benefit from temperature gradients in the water that keep the hotter water at the top surface of the pond.

Cooling performance is dependent on the ponds being full irrespective of flow rate into the pond. The water level is maintained by a level control at the outlets of the

the ponds. On the hot ponds the water level is controlled by the inlet into the cool pond. The cool pond level is maintained in the case of the Well 5 cool pond by the intake into the gravity conveyance pipeline, and for Wells 1, 4 and 6 the conveyance pump controls incorporate a level control switch in the cool pond. The level switch automatically starts the pump when the water level reaches full supply level and stops it if the level drops 200mm below full supply level. Then the full flow water is gathering from all cooling ponds and discharge to two reservoirs their capacity 35000 35000 m³ for each, to reduce the water temperature again from 40°C, then water is pumped by pump station and control system via the irrigation network to the pivot machines for water spray in the crop fields, the total amount of irrigation water can be producing is 21,410 m³/day as shown Figure 2.9.

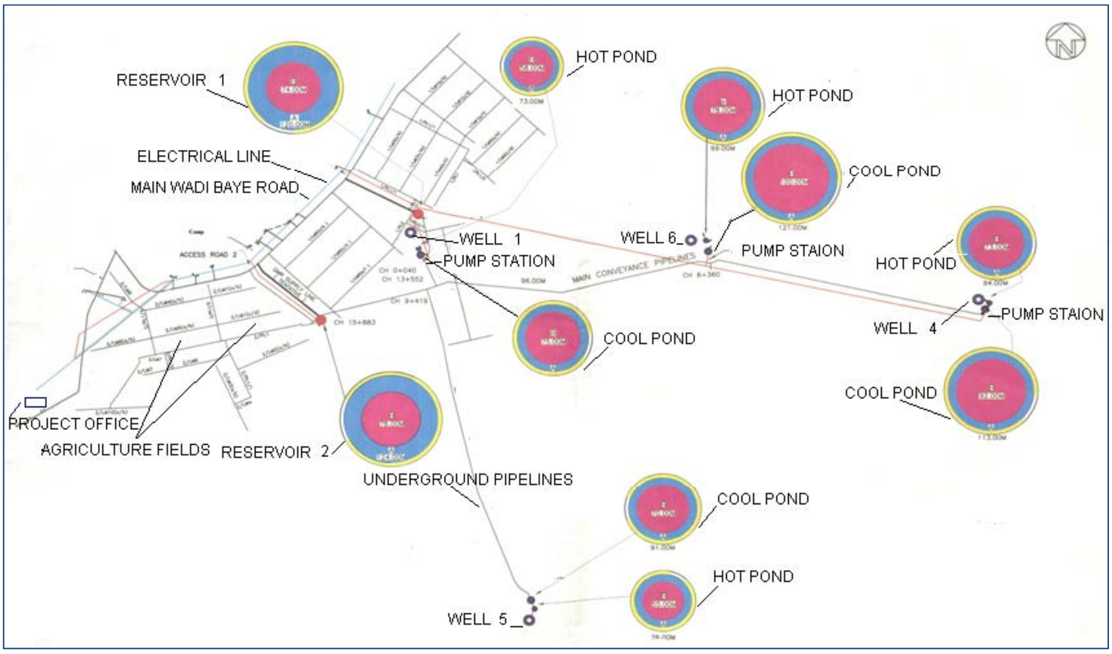

Figure 2.9 The irrigation system: groundwater abstractions and cooling ponds

2.4.5 Summary: groundwater in Wadi Baye

It is clear so far that groundwater is the only available water supply for human use, agriculture at the moment. The Ministry of Agriculture and other related local agencies are looking at potential of the further groundwater supply to wider scope. Therefore the available quantity in a sustainable manner and also it quality for the needs are timely important issues for further understanding.

It was anticipated that a complete understanding of the aquifer system, groundwater resources, and its quality in terms of hydro-geochemical evolution in the Wadi Baye catchment can be achieved through this PhD project. It was also understood that little existing data was available and much effort is required subject to the limited time and resources available for a PhD project. The numerical modelling was then chosen as a more cost-effective approach to understand the groundwater system. It was also envisaged that some useful finds can be inferred from this study so that further groundwater investigation in the earlier said Wadis, e.g. Zamzam, Baye, in the northern Libya can be promoted in the near future.

2.5 The State-of-art Research Issues

Researches related to assessment and management, exploitation & utilization of groundwater resources were performed in past decades. However, much more attention should focus upon the following related issues in arid region, as per such a study for this project.

- The climate change and global warming are increasingly remarkable. Precipitation in arid region will be scarcer and groundwater system will not get enough recharge. The eco-environmental vulnerability in arid region will be much more serious, and the climate changes maybe hamper the exploitation & utilization of groundwater resources. It will be of great significance to cope with those various difficulties in the future research.

- Human activities can change the groundwater circulation, such as change in recharge process by over-withdrawal, non-point contamination from agricultural and industry activities and sea water intrusion by over-exploitation. These can affect the sustainable utilization of groundwater resources and studies on such human activities should be addressed.
- To solve the above mentioned problem in a more costs-effective way, integrated groundwater modelling techniques should be employed. These can also produce much more scenario with less investment for decision making.

Chapter 3 DESK STUDY: WADI BAYE

3.1 Site Location

Wadi Baye lies in the northern coastal region of Libya, neighbouring Mediterranean in the north, which geotectonically belongs to North African Platform. The Wadi Baye Valley covers a triangle area of 57,800 km^2 with width narrowing from south to north. As shown in Figure 3.1, a major NNW-SSE trending fault system – the Hun Graben-forms a significant geological boundary between the Sirte Basin and Hamada Al Hamra Basin further to the west. In this vast flat region, the altitude in the south is generally higher than that in the north except for some steep parts near the Hun graben.

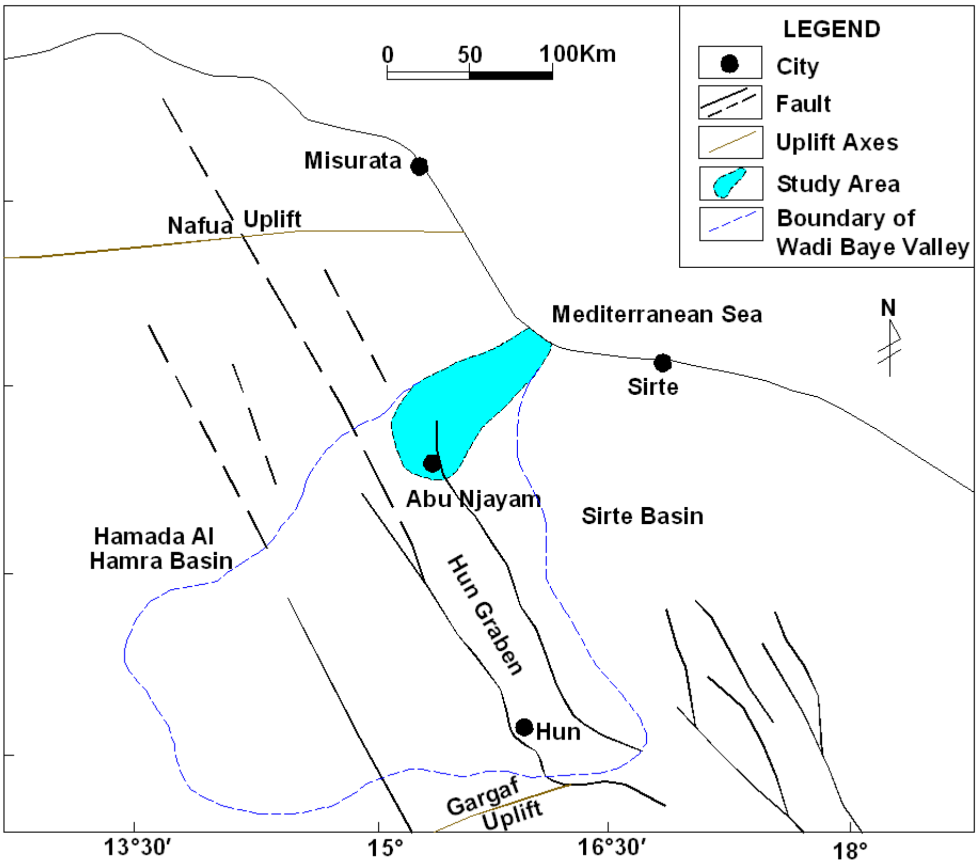

Figure 3.1 Location of Wadi Baye

The study area is located in the downstream of the Wadi Baye catchment between 15° -16°10′E longitude and 30°30′ -31°20′N latitude, covering an area of about 3,650 km^2 from the Hun graben to Mediterranean. Wadi Baye Al Kabir flows from southwest to northeast, and finally into Mediterranean (Figure 3.2). There is a convenient transportation network in the study area for accesses of field investigations and samplings.

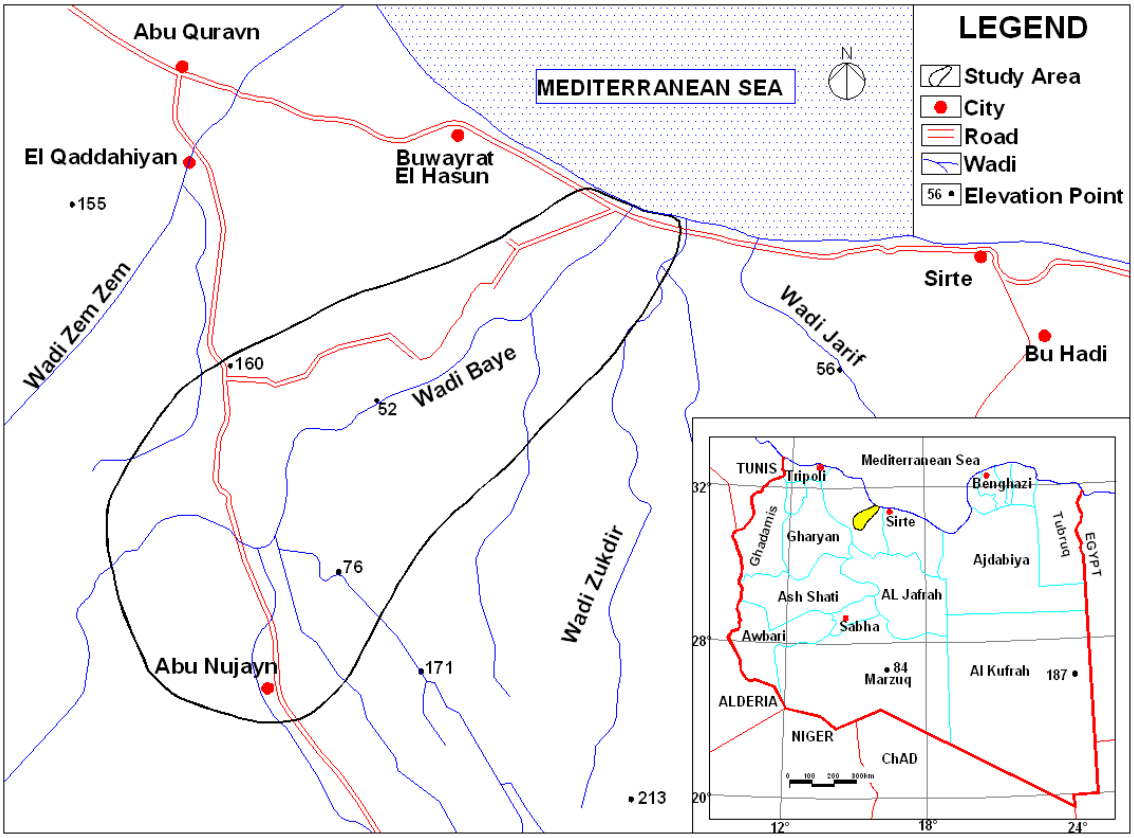

Figure 3.2 Location of the study area

3.2 Physical Geography

3.2.1 Climate

Situated in the transition zone between the Sahara and Mediterranean, the climate represents typical continental arid and semi-arid features with little rainfall, hot and dry weather in summer and warm and rainy in winter. Climate change varies from region to region. There is little available meteorological data; the meteorological data in this area comes mainly from four weather stations: Sirte，Abu Misurata and Hun which locations are shown in Figure 3.3.

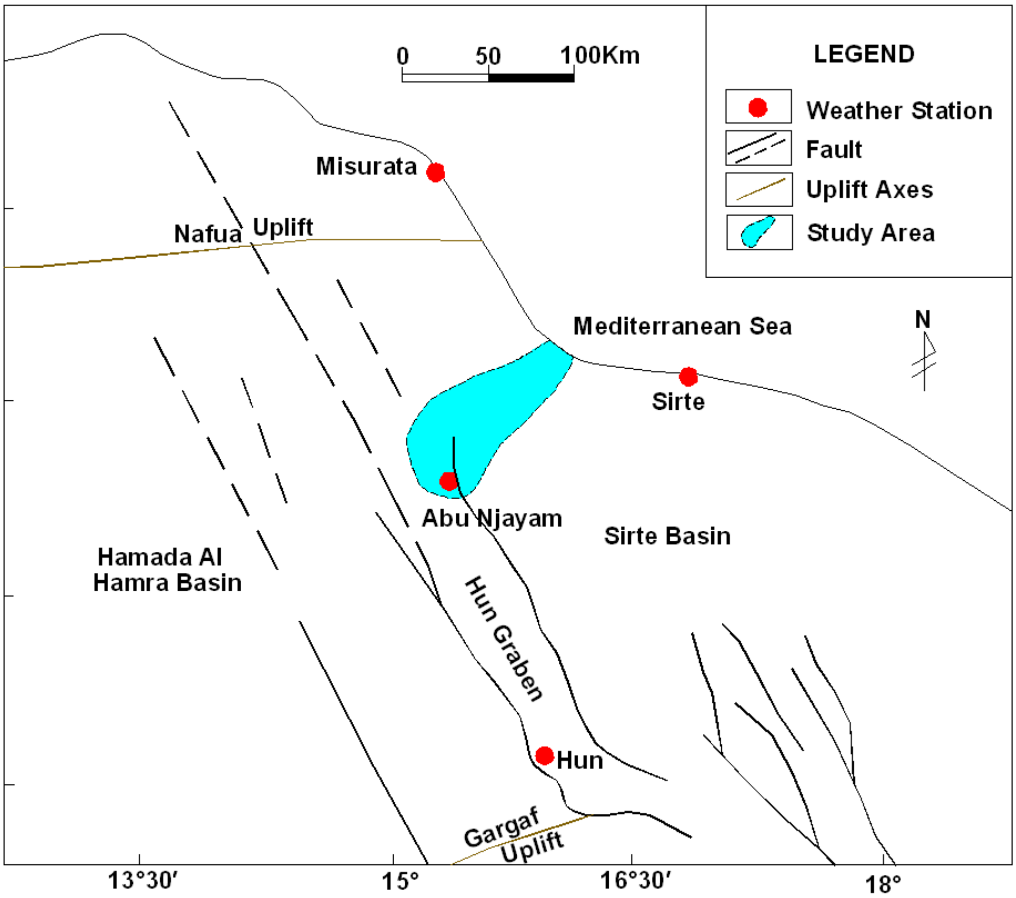

Figure 3.3 Distribution of the weather stations

1) Temperature and Humidity

The average annual temperature is 21.6°C. Figure 3.4 shows the annual average temperature in the south is 22.2°C, a little higher than that in the north. Moreover, it can be seen that January is the coldest month with 13.8°C and that August is the hottest month with 26.9°C.The annual insulation duration is 3250 h with the longest time during June to August and shortest during December to March. There is no frost period all over a year.

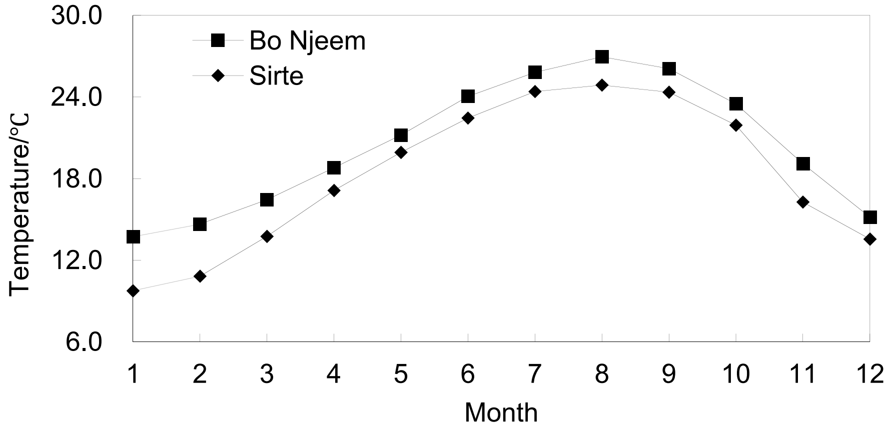

Figure 3.4 Temperatures variation in one year at Station Sirte and Abu Njayam

The average relative humidity of the atmosphere decreases from the coast to the inland. The highest humidity can reach 66-76% near the sea, whilst it is only 49 --59.3% inland. Variations were recorded throughout a year that the lowest appears in summer at inland weather station Abu Njayam while at Sirte near Mediterranean it is just the opposite (Figure 3.5).

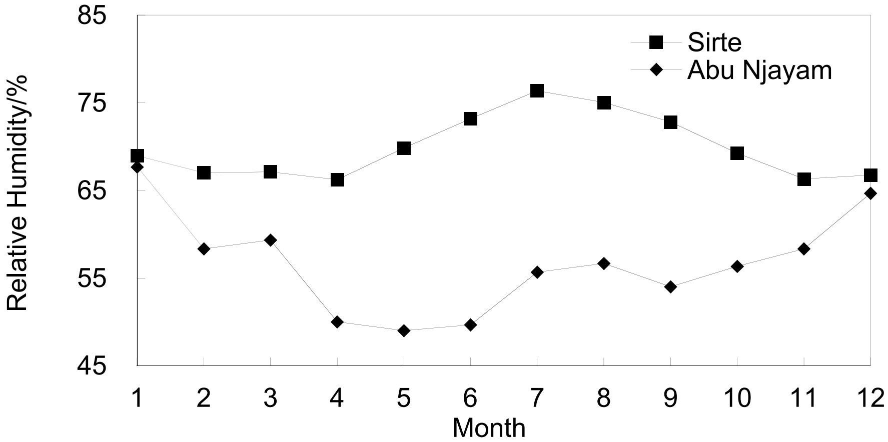

Figure 3.5 Humidity variation in one year at Station Sirte and Abu Njayam

2) Precipitation and Evaporation

Affected by geographic location and topography, mean monthly precipitation is unevenly distributed. Due to the data are only from the limited four stations, these following diagrams show a trend of extrapolation of these four points. The average annual precipitation decreases from 170 mm in north to 100 mm in south with the distance away from the coast (Figure 3.6). 90% of the total precipitation concentrates in autumn and winter (Figure 3.7). Besides, inter-annual variation is obvious according to the records at Sirte. In 1970s, average rainfall was 213 mm, and it decreased to 190 mm in 1980s, followed by a slight increase in 1990s. However, the figures showed a steady decline after 2000.

Contrary to the changes of precipitation, annual average evaporation increases from 1701 mm to 2607 mm with the distance away from the coast (Figure 3.8).

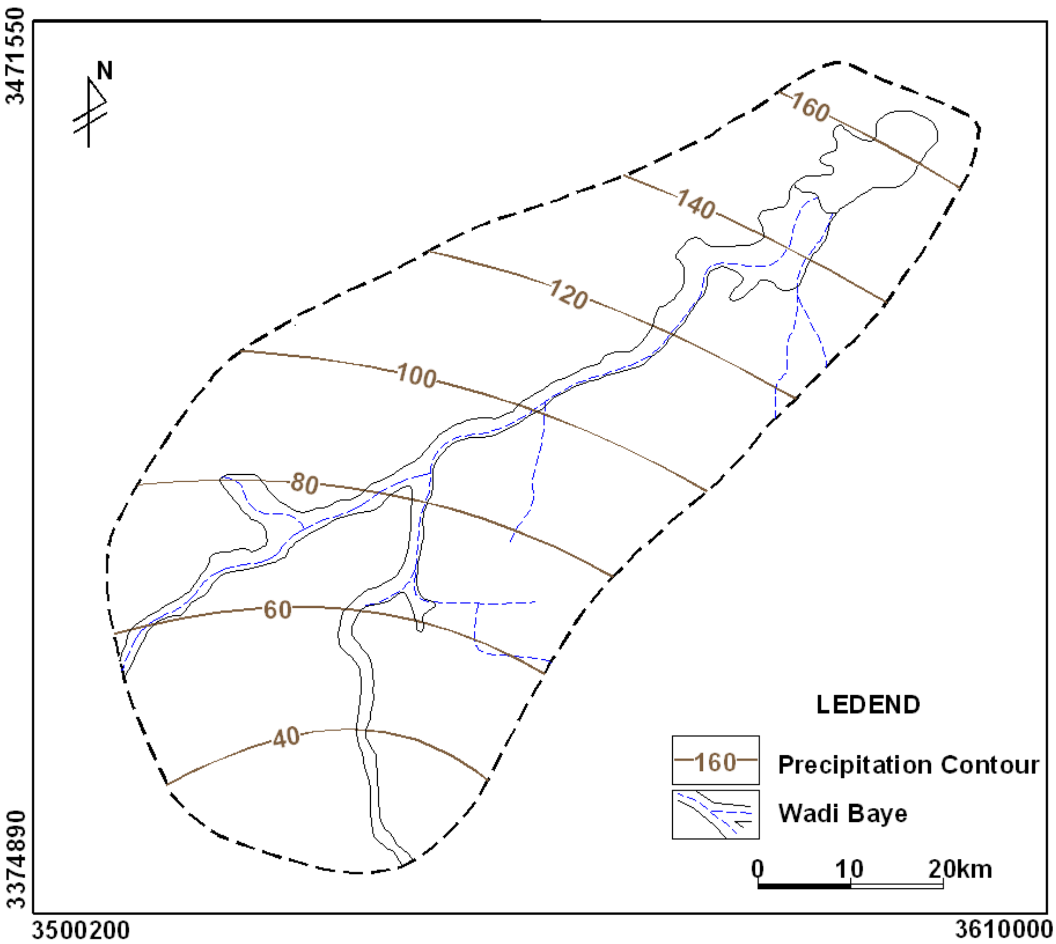

Figure 3.6 Distribution of average annual precipitation in the study area

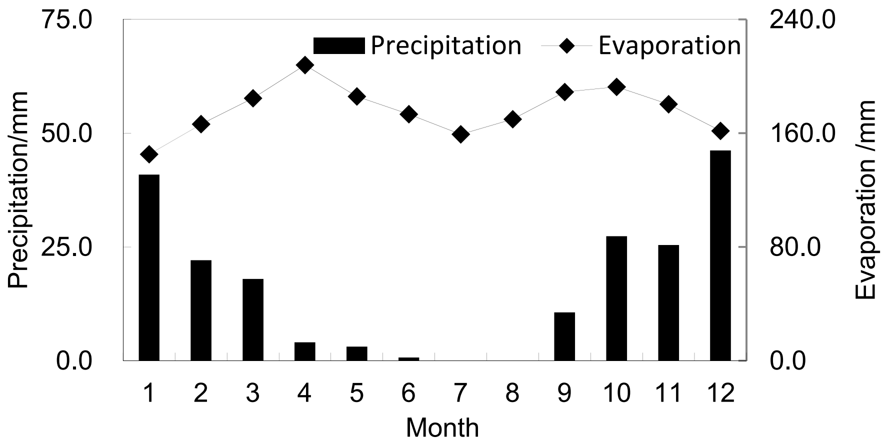

Figure 3.7 Variation of precipitation and evaporation at Sirte in one year

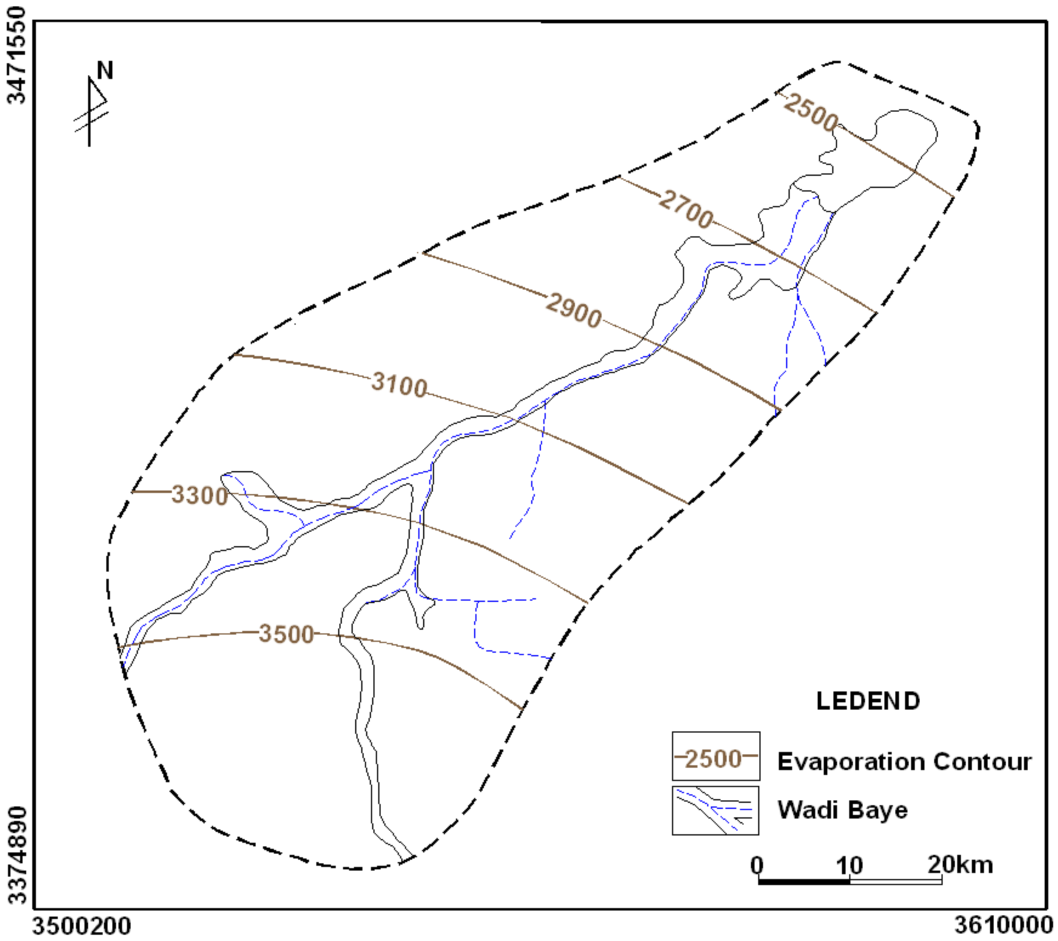

Figure 3.8 Distribution of the average annual evaporation in the study area

3.2.2 Hydrology

The Wadi Baye Al Kabir is a fossil of the Pleistocene period; nowadays, the vegetation and morphology clearly show that it is no longer the scene of a frequent generalized water-flow, the absence of a minor riverbed and of recent alluviums. According to the statement of the local inhabitants, water can be observed in it once every two years on average. One the other hand, traces of recent erosion have been ascertained in the thalwegs flowing towards it, where the longitudinal slope is more pronounced; trickles of water must appear after local rainstorms but as soon as they reach the main valley, they must as often as not, spread out and seep away.

Since the surface water resources are so little that it can be negligible, water resources in Wadi Baye is groundwater, which is available in the following three strata:

- Eocene limestones/dolomites (Tertiary age)
- Gharian or Nalut Dolomite (Upper Cretaceous age)
- Kikla Sandstones (Lower Cretaceous age)

Groundwater flow in the Eocene aquifer is minimal (c 7 l/s per km of flow path width) and the quality is poor (for the old camp well, TDS = 8500 mg/l). Very poor yields were determined in the Ghjarian/Nalut from testing during drilling down to the Kikla in the 1970s, although water quality is reasonable (TDS 1600-2000). The Kikla is a confined aquifer with groundwater levels above ground surface. It is considered therefore that Kikla aquifer represents a major water source for irrigation in this area.

Depending on the water sources from the Kikla aquifer, 2 reservoirs were built to meet the agriculture water demand. For each pumping well (as shown in Figure

3.9), 2 pools were used for water cooling as the temperature of groundwater in Kikla is so high as 78°C that it's unknot suitable for direct irrigation. After the cooling process, water discharges into the two reservoirs. The storage capacities and flow rates of the two reservoirs are summarized in Table 3.1.

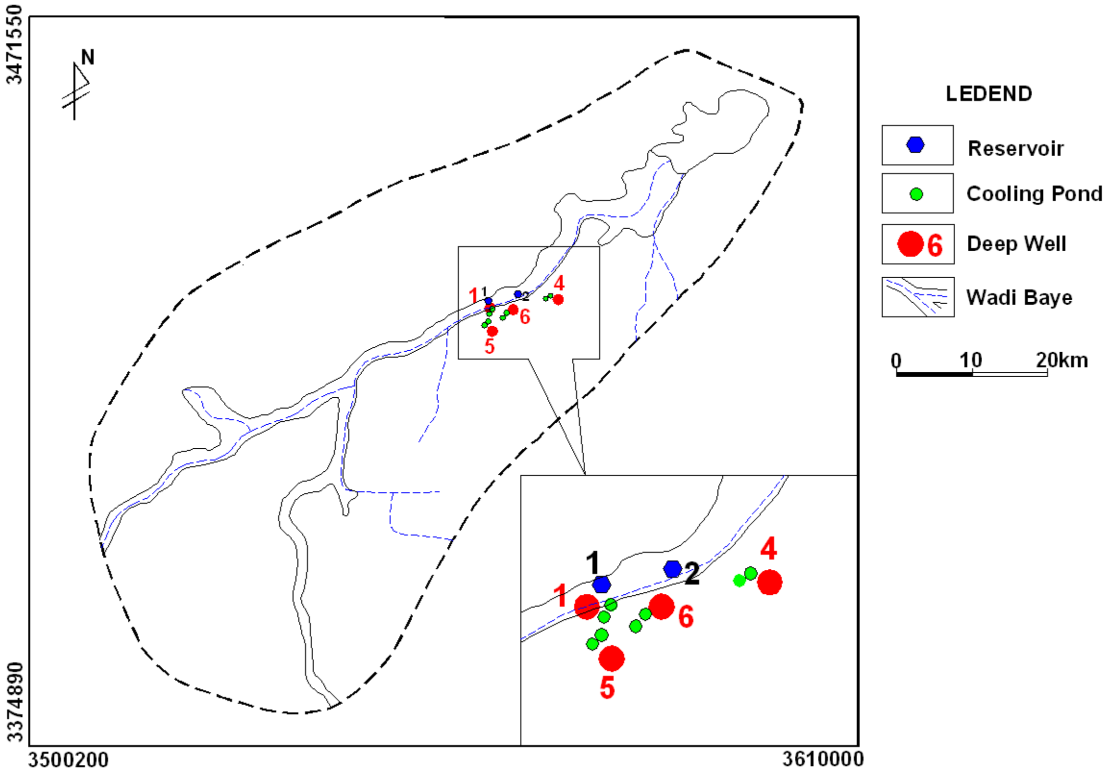

Figure 3.9 Distribution of reservoirs, pumping wells and cooling pools in Wadi Baye

Table 3.1 Characteristic parameters of reservoirs

Reservoir	Peak Discharge (l/s)	Storage capacity for 12 h (m^3)
1	405	17,496
2	489	21,125

3.2.3 Topography

The study area is an alluvial plain with relatively gentle topography. It gently dips from southwest towards northeast with topographic relief in some places. The topographic variation is estimated 1-2 m, and the gradient is general held less than

0.5%. In the northeast of the study area, the topography is flat. There is a seasonal lake at the edge of entrance to the sea, whose elevation is less than 10 m. In the central the elevation goes up slightly, varieties between 10-100 m, and reaches 150 m to the highest. It is consisted with many dry valleys whose depths are almost 30 m. These wadis are composed by Quaternary deposits came from either river accumulation or aeolian sediment. Most of the sediment is fine sand or fine silt. Wind erosion plays a decisive role in the formation of the landscape features, accordingly most parts of the area are covered by sand dunes now. The sand dunes with low and flat hill top, show that a formation in varying solid degrees with difference in ability of weathering resistance. The south-western of study area is composed with northern part of the Hun Graben and the edge of western part of the Sirte basin, which is estimated 100-200 m in elevation. The gradient of the region is nearly 0.2%.

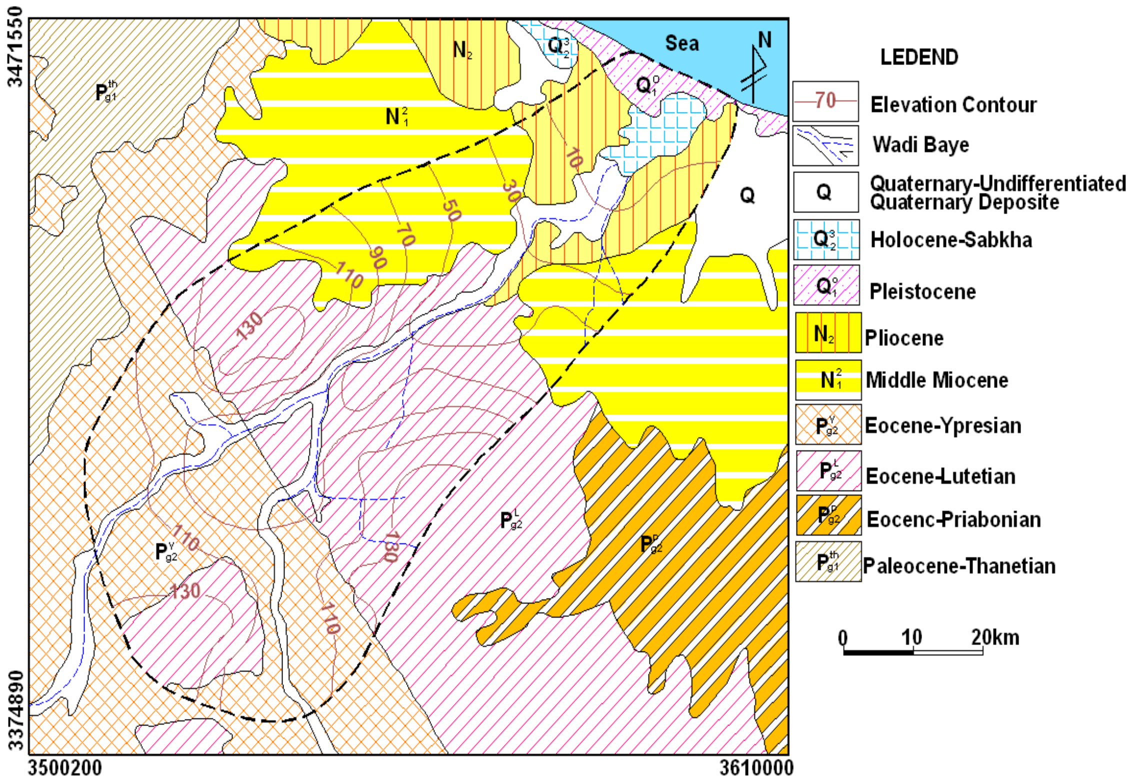

Figure 3.10 Topographic map of the study area

Based on the previous investigations, a topographic map of the study area was drawn and shown in Figure 3.10 with more data collected to make the map from Google Earth. We tried to collect a DEM/DTM from the related Ministries or Agencies but it has been not successful unfortunately. This however could be some usefulness for future study, particularly for GIS-based water management.

3.3 Geology

3.3.1 Stratigraphy

Formations of the Devonian, Cretaceous, Tertiary and Quaternary Periods compose the geological system in the study area. Along the coastal strip and Wadi Baye, the platform type Quaternary deposits are present. The Tertiary deposits are outcropping in the rest parts of the region (Gefli, 1773; IRC, 1985; Halcrow 2001). The detailed information about the formation is described in the following sections.

1) Tertiary

a. Paleocene

There are two formations of Paleocene existing in the study area, namely Zimam Formation and Shurfah Formation.

The Zimam Formation is the oldest formation cropping out in the par of BuNjim area, and represented only by its uppermost member (Had Member). The thickness of this member in its type section is 50m. In the study area, only the upper part of Had Member represent whose depth is about 8m, while the lower boundary is not exposed. The Had Member crops out only at the southwestern corner of the and has relatively a small aerial extent. In most of the cases it forms the floor and the banks shallow wadis. The Had Member consists of well bedded dolomitic limestone, calcilutite and limestone marly in some parts. The common character of the member is the relatively high content ratio of dolomite (MgO).

The other formation is Shrufah which consists of the Bu Ras Marlstone Member and Qaltah Member. Bu Ras Member occurs mainly west of the western flank of the Hun Graben. It forms gentle slopes and few conical hills overlaying the Had Member. In the study area, the Bu Ras Member consists of grayish yellow soft marl, creamy white soft calcilutite marly at parts, white hard chalky limestone and yellowish white hard fossiliferous limestone. The thickness of the member in this location reaches 20-25 m, and has a gradual decreasing trend to north and west.

According to the information, the Qaltah Member distributes the south part of the area, and it is cropping out only at the western Hun Graben Fault, forming the walls of the relatively deep wadis and the plateau surface. The member consists of a sequence of limestone, marly limestone, chalky limestone with intercalations of calcarenite and calcilutite. The Qaltah Member shows little variation in the thickness where ranges from 45-55 m.

b. Paleocene-Lower Eocene

This system contains two formations that are Bishimah Formation and Undifferentiated Bishimah Formation. These two formations both exist in the southern part of the study area.

The Bishimah Formation changes in its facies from the northwest to the southeast. In the northwestern corner, the deposits of the formation underwent a simple lithologically undifferentiated development, whereas along the eastern scarp of the Hun Graben it shows different lithological characters that can be divided into three members, which are Khayir Member, Wadi Zakim Member and Rawaghah Member. First, the aerial extent of Khayir Member is relatively limited. It occurs in the southwest of the region where along the eastern scarp of the Hun Graben Fault. The lithology of this member is pale greenish yellow gypsiferrous marl, marly limestone with interbeds of calcarenite and calcilutite. The thickness is 25 m around and gradual down to the north. Second, the Wadi Zakim Member outcrops along the eastern scarp of the Hun Graben where is in the southwest of the region. The member consists of chalky limestone, chalk with the bands of dolomitic limestones and calcilutite with thin bands of dolomitic limestones, with chert concretions at the upper part. The thickness of this member various from 18-28 m, the thickness decreases towards the northwest. Third, the sequence of the Rawaghah Member sediment is white chalk, chalky limestone, limestone and siliceous with chert bands, nodules and concretions. The thickness is about 35-40 m, increase to 60 m to the southeast.

The facies of the Bishimah Formation is only outcropping in the southwest of the study area. The formation consists of limestone, chalky limestone, marly limestone and siliceous limestone with chert nodules, which ranging between 40-50 m, and decreases to the southwest direction. The slope of the formation is less than 3°.

c. Lower Eocene-Middle Eocene

Al Jir Formation is a unique formation of this system in the study area.

The Al Jir Formation in this area shows lateral change in thickness and lithology. It presents from the central part to the southern part of the region. In the central part of the area, the formation shows its maximum thickness, there are two members developed and can be easily traced in the field. However, the thick of the unit decreases toward to south, especially the lower member till it become very difficult to be separated the formation into two members.

One is Bin Isa Member that consists of a sequence of white to yellow and hard limestone with interbeds of sandy limestone and marly limestone with gypsum at parts and capped by light grey, hard, compact and siliceous limestone bed containing chert nodules and concretions which are mainly concentrated at the lower part of the bed. The thickness is 24 around.

The other is Bir Zayden Member consisting of sequence of marly limestone and limestone. The section starts by a marly limestone bed, about 1m thick, very rich with the Orbitolites complanatus Lamarck, and other fossils, overlain by white to creamy white to creamy white marly limestone, followed by a sequence of creamy limestone beds with horizons rich with macrofossils, cavernous with color changing to brownish yellow at parts and hard compact white limestone. The thickness of the member is about 27 m.

d. Middle Eocene-Upper Eocene

This system refers to Wadi Thamat Formation in this area. The Wadi Thamat can be divided into two parts. The lower part consists of marly limestone and sandy marly limestone, while the upper part consists of marly limestone and limestone with chert concretions. The maximum of its thickness is 73 m.

e. Middle Miocene

The Al Khums Formation of this system presents in the northern part of the study area, the thickness is about 20-30 m which can be divided into two parts. The lower part consists of limestone and sandy limestone, as well as the upper part of the formation consists of marly limestone, marly limestone with gypsum and porous limestone.

The Old Wadi Terraces occur along the banks and beds of Wadi Baye, and consist of a well-cemennted conglomerate, with interbeds of coarse to fine-grained sandstone. The conglomerate is usually 1~15 m, and grayish green in colour; the sandstone interbeds are mostly 10~20 cm thick.

2) Quaternary

The Quaternary deposits cover a considerable part of the study area. It can be differentiated into Sabkha sediments of Pleistocene age and the Fluvio-eolian deposits, Wadi deposits and Eoljan deposits of Holocene age.

a. Pleistocene

Two types of Pleistocene deposits occur in Al Qaddahiyah area: Caliche and Gargaresh Fomation.

Caliche is a characteristic calcareous crust which occurs on the surface of practically all rock types in the investigated area. It consists of a reddish-brown to light-brown sandy limestone, very compact and usually tabular. Its thickness is generally only 10~20 cm, very rarely up to 1~2 m.

Gargaresh Formation occurs along the coastal belt, and consists of calcarenite, with frequent interbeds of well-cemented eolian sand.

b. Holocene

Five different Holocene deposits (the sabkha sediments, fluvio-eolian, eolian, and recent wadi deposits, and beach sand) were identified in the study area.

Sabkha Sediment mainly presents in the northern part of the study region, general inside of the seasonal lake and coastal tectonic zone. The thickness and bound of the Sabkha Sediment various with the location and size of the seasonal lake. The sediment can be departed into three levels. The lowermost level consists mostly light-gray sand with salt. The sand is similar in color, grain size, and about0.2-0.6 m. The next level consists mostly of silt, black mud and clayey material, with a minor amount of salt. The thickness of this level is between 0.05-0.3 m. The uppermost level consists of red clay with salt and gypsum, mostly on the surface.

Fluvio-Eolian Deposits are widely covering the plain and filling up the flat and broad wadis. They are always made up by fine-grain sand, silt with thin intercalations of gravels of variable degree of rounding. The thickness of these deposits various from 1 to 10 m.

Eolian Deposits are considered as the youngest deposits in the southern part of the study area. The eolian deposits accumulate in the form of sand dunes. These deposits mainly consist of pinky and light over dark sand whose the gain diameter is 0.1-0.2 mm around, well sorted. Most of the grains are carbonate with plenty of quartz. The thickness of the deposits is usually less than 1m.

Recent Wadi deposits occur along the courses of Wadi Baye, and consist of non-cemented, fine to coarse grained sand and some gravel. The composition is not uniform and depends on the rock types present along the particular wadi, and the general thickness is 1-5 m.

Beach sand occurs along the present coast line only, and consists mostly of light-gray sand, produced by the weathering of the Gargaresh Formation, with highly abundant shell fragments. The sand content increases with the distance from the coast line. The stratigraphic succession for this area is described in Figure 3.11.

3.3.2 Tectonics

There are three structural units in the study area: the eastern Sirte Basin, western Al Hamada al Hamra Basin and southern Hun Graben, which determine the structure of the whole region.

In the northern part of the study area, the landform is wide coastal plain, and the distribution of the stratum is horizontal or sub-horizontal. The sediments are undisturbed and no fold-type structures were formed except some faults.

In the southern part of the study area, the stratums have fluctuation, but the hypsography doesn’t exceed 1-2 m. The fold has not developed there. However, there are obvious north-west toward faults due to the influence of the Hun Graben structure. Therefore, the mainly type of structure in this area are faults, which are illustrated in Figure 3.12 (IRC 1985).

Deep (m)	Thick (m)	Log	Description
0	76		Limestone, yellowish
76	22		Limestone, white-yellowish
98	92		Dolomitic limestone,greyish-yellowish,porous
190	30		Dolomite, porous, grey, withinterbeds of marl
220	32		Marl and limestone interbeded
252	53		Dolomitic limestone, grey, porous, with gypsum
305	108		Dolomite,grey
413	71		Marly clay, dark grey, with interbeds of dolomite
484	41		Marly limestone, dark grey
525	467		Marly shale, grey-dark grey with marl, limestone and dolomite interbeds
992	90		Dolomitic limestone at the upper part, dolomite at the middle part, imestone at the lower part
1082	22		Marl, with the interbeds of limestone at the lower part
1104	60		Shale, dark grey-black
1164	22		Marl , with clay at the lower part
1186	242		Sandstone, fine-middle grain, with quartz, with shale and clay interbeds

Figure 3.11 Stratigraphic succession at a borehole (Code T/2D/0010/0/83)

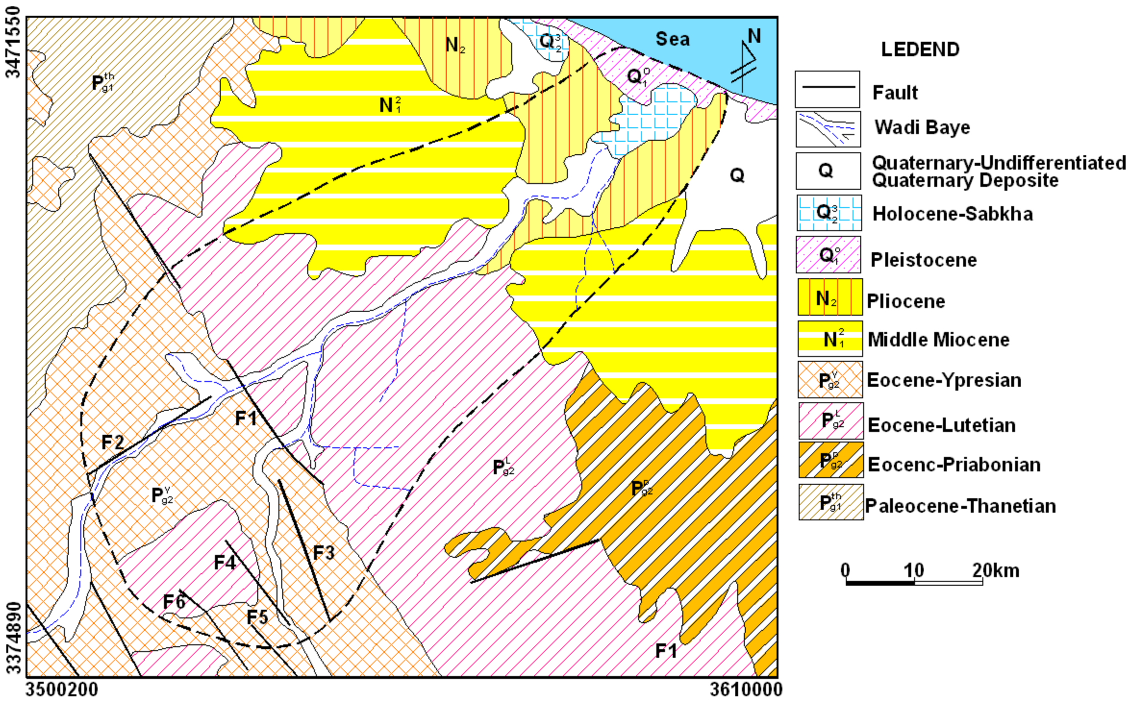

Figure 3.12 Distribution of faults in the study area

F1: The normal fault occurring in the Paleocene strata, composed mostly of limestone, marly limestone. The fault strike is 323°, dip to SW, and the two plates of the fault are Al Jir Formation and Bishimah Formation.

F2: This normal fault distributes along the wadi Bayes whose strike is 58° dipping toward SE at about 80 degree. This fault occupies inside of Bishimah Formation of Eocene unit. The mainly lithology is marly limestone, limestone, chalky limestone and sandy limestone.

F3: The normal fault occurring inside of Bishimah Formation of Eocene unit, with strike of 338°, dip to NE.The lithology is mostly of marly limestone, chalky limestone and sandy limestone.

F4: This normal fault occupies southwestern part of study area, whose trend is 317°, also dip toward NE. A part of it developed in Al Jir Formation, while the other part is inside of Bishimah Formation. The mainly lithology is marlite, marl limestone and limestone.

These faults can potentially create very good opportunity to groundwater movement and also storage. These have been considered in the following conceptualisation and modelling study (e.g. assignment of hydraulic conductivity *K*). Further hydrogeological significance of these faults might be further studied by geophysical surveys.

3.3.3 Stratigraphic Model

Groundwater Modeling System (GMS) is one of the most sophisticated and comprehensive groundwater modelling software. Used by thousands of people at U.S. Government agencies, private firms, and international sites in over 90 countries; and it has been proven to be an effective and exciting modelling system. GMS provides tools for every phase of a groundwater simulation including site characterization, model development, calibration, post-processing, and visualization. GMS supports both finite-difference and finite-element models in 2D and 3D including MODFLOW MODPATH, MT3DMS/RT3D, SEAM3D, ART3D, UTCHEM, FEMWATER, PEST, UCODE, MODAEM and SEEP2D. The GMS interface was developed by the Environmental Modeling Research Laboratory of Brigham Young University in partnership with the U.S. Army Engineer Waterways Experiment Station. The program's modules were designed in a comprehensive modelling environment. Several types of models are supported and facilities are provided to share information between different models and data types. Tools are provided for site characterization, model conceptualization, mesh and grid generation, geostatistics, and post-processing.

In this study, GMS was applied to construct a stratigraphic model for the study area. Detailed procedures are as follows:

- All the available geological data including three geologic profiles, a geological map at the scale of 1:100000, and stratigraphic succession of 10 deeps were combined and digitalized to a readable file for GMS.
- The digitalized file was imported into Borehole module embedded in GMS with specified a material ID number for each section of each borehole. GMS created material with those IDs and gave them default names and colours.
- Blank cross sections were auto created by connecting the same ID of each borehole. Then, these sections were filled with different colours after manual revision.
- Solid module was used to construct 3-D models of stratigraphy from horizon according to borehole cross section data.

The 3-D stratigraphic model of the study area is shown in Figure 3.13, in which the scale of vertical direction is magnified tenfold in order to achieve a better view.

In GMS, more images could be obtained including (1) stratigraphic structure images from different viewpoints (Figure 3.13a, b), (2) cross sections cut at anywhere of the model (Figure 3.13c), (3) 3-D shape of each formation (Figure 3.13d), (4) horizontal sections at different elevations. Besides, GMS provides geometric calculation function for strata, as well as more complex arithmetic operation such as groundwater storage by the multiplication of porosity and the volumes of layer saturated by water. However, the precision of these calculations will decrease to an extent as the result of the simplified geological structure in the model. Unfortunately due to time constraint the faults were not shown in the GMS model; but this solid model was just showing the conceptual understanding of sedimentation geology.

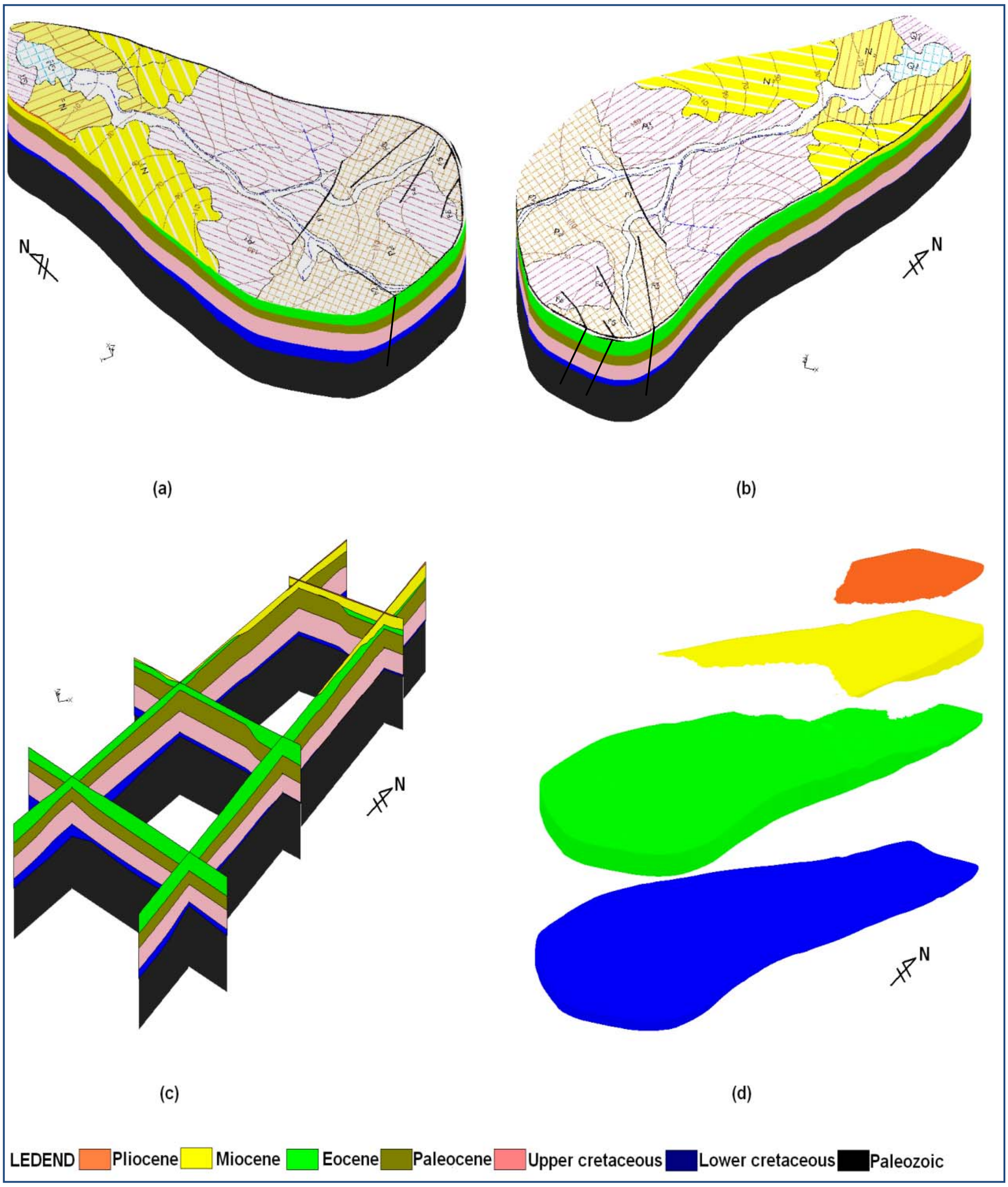

Figure 3.13 The 3D stratigraphic model of Wadi Baye

3.4 Hydrogeology

3.4.1 Aquifers

There are five aquifers in the study area, that being 1) Eocene aquifer, 2) Miocene aquifer, 3) Upper Cretaceous Mizda aquifer, 4) Upper Cretaceous Garian aquifer, 5) Lower Cretaceous Kikla aquifer (Sandstones). Not all these aquifers are confined. According to the buried conditions, the former two Tertiary aquifers are classified to be unconfined, while the latter Cretaceous ones are confined.

1) Tertiary age

Miocene and Eocene aquifers were discovered in this area.

The Miocene aquifer occurs widely in Al Qaddahiyah sheet of coastal area. From the lithological point of view, this aquifer consists of limestone, marly limestone and calcarenite. Its thickness ranges between 40m and 120m.

The distribution of Eocene aquifer is mainly widespread inland. Lithologically the aquifer consists of limestone, marly limestone, dolomite and local gypsum. Its thickness ranges between 30 and 200m. Its yield strongly depends on the degree of fracture development.

2) Cretaceous age

Three Cretaceous aquifers occur in this area, which are Upper Cretaceous Mizda aquifer, Upper Cretaceous Garian aquifer, and Lower Cretaceous Kikla aquifer.

Mizda aquifer is composed by limestone lithologically. The groundwater quality is poor with TDS increasing from 3000 mg/L in the inland to 30000 mg/L in the coastal region. Its thickness ranges extremely from 48 m to 276 m. The depth of groundwater table varies between 548 m to 933 m.

The Garian aquifer is widely distributed in this area, which mainly consist dolomite, limestone, dolomitic limestone, and sandy limestone. The elevation (above the Sea) of groundwater table ranges between 690 m to 1177 m with the thickness of 65~150 m. Very poor yields were determined in the Ghjarian/Nalut from testing during drilling down to the Kikla in the 1970s, although water quality is reasonable for TDS between 1600 mg/L and 2000 mg/L.

The Lower Cretaceous aquifer refers to Kikla sandstone aquifer extending over some 50% of the country, which is the main current source for domestic and agricultural water supply in Libya. It is artesian but very deep (1,210 m ~1,574 m) and supplies water which is only slightly mineralized (1530 mg/L) but at high temperature at more than 60°C. Typical cross sections are shown in Figure 3.14~Figure 3.17.

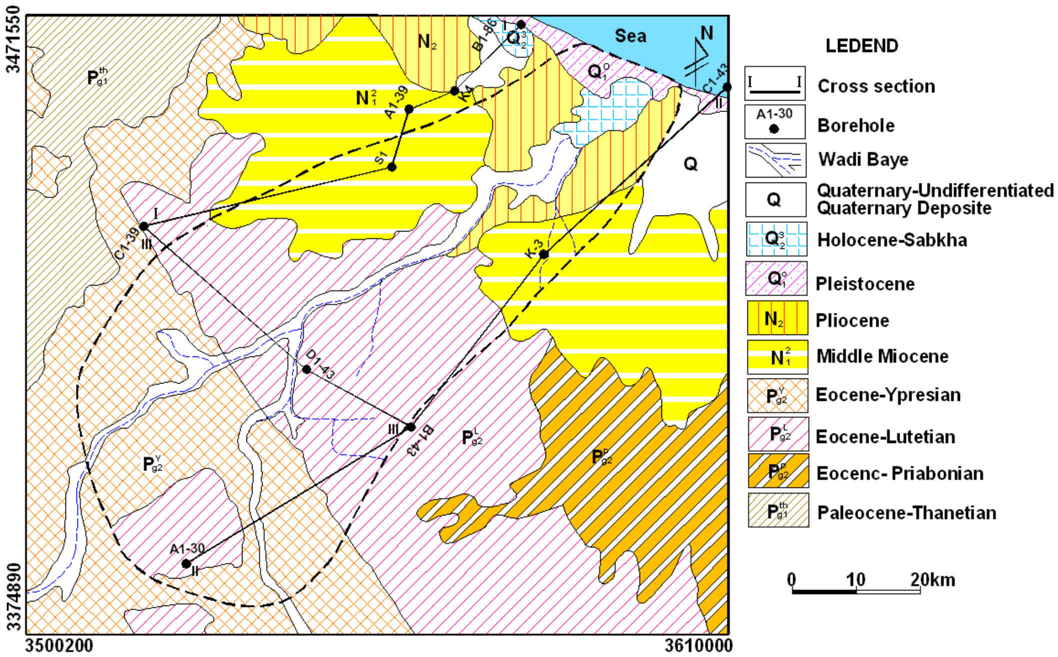

Figure 3.14 Crosse sections of the Wadi Baye geological description

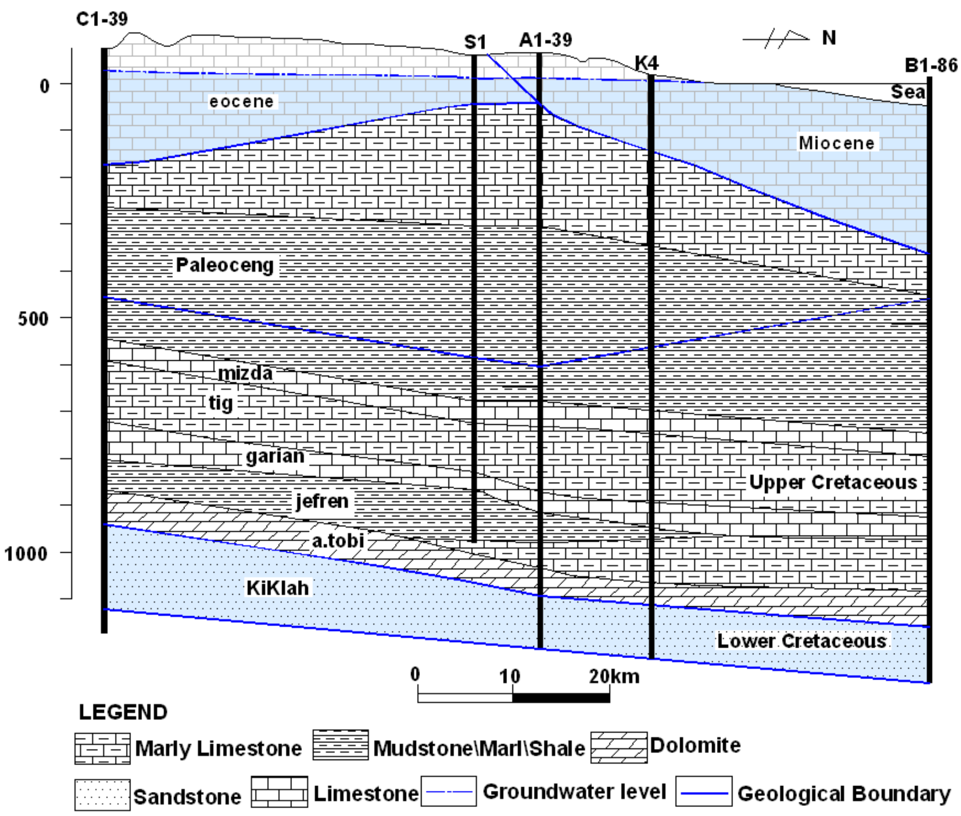

Figure 3.15 Cross section I-I' of Wadi Baye

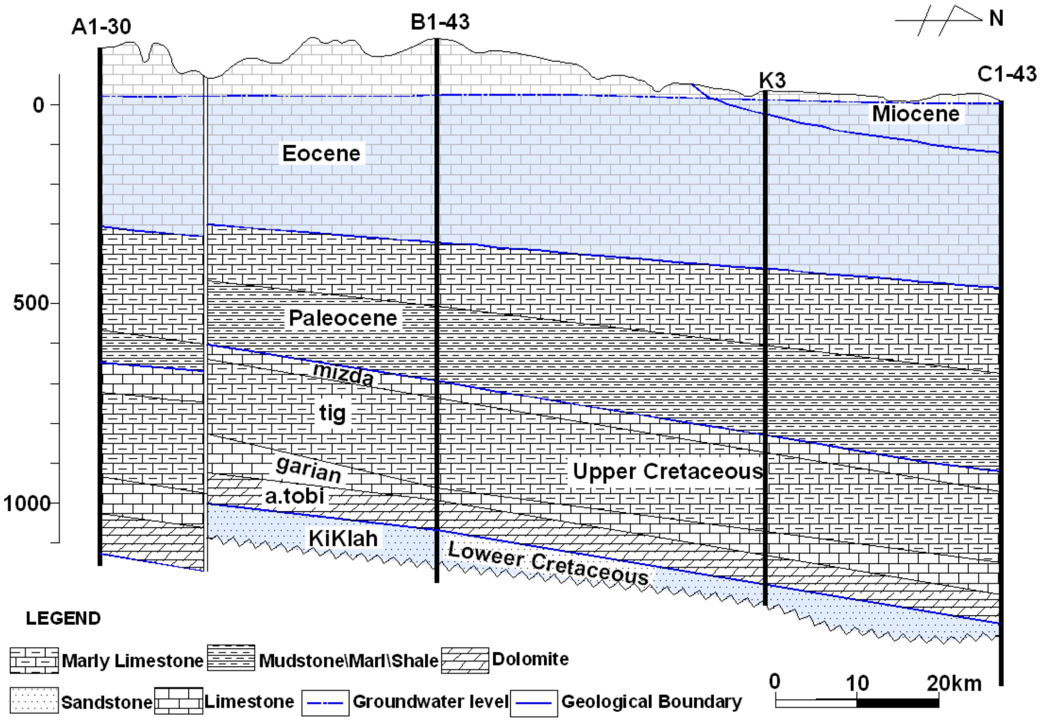

Figure 3.16 Cross section II-II' of Wadi Baye

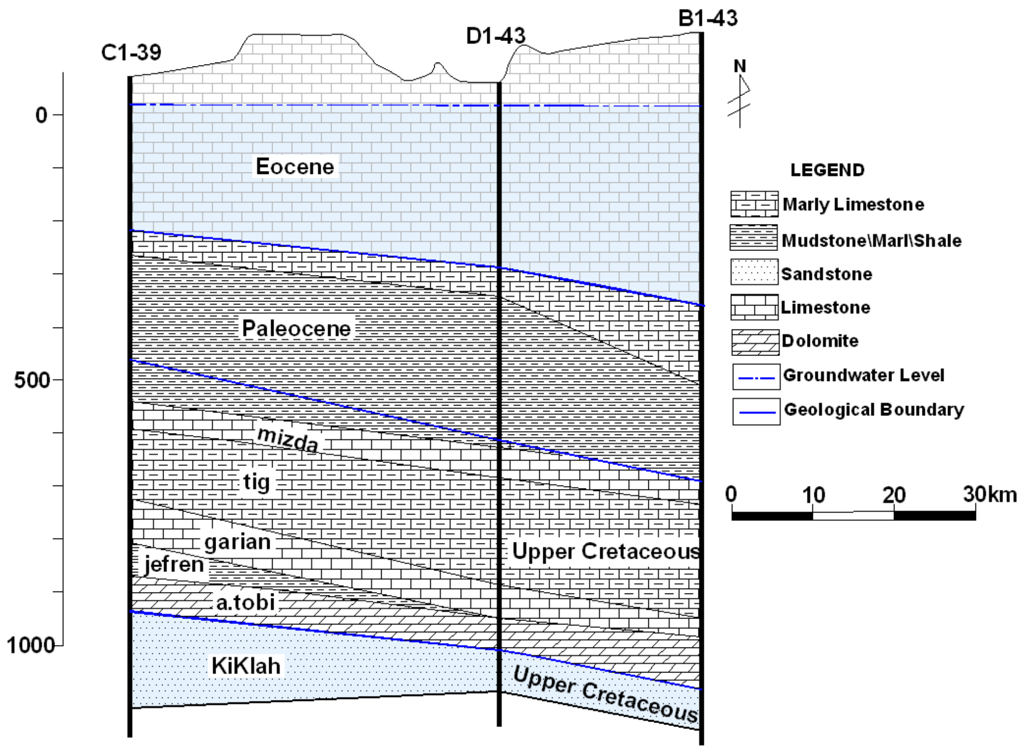

Figure 3.17 Cross section III-III' of Wadi Baye

3.4.2 Groundwater Circulation

The only water resource in Wadi Baye is groundwater, and most groundwater production is from Eocene and Kikla aquifers. The circulation characterisations of groundwater in the above aquifers are described in detail below.

Generally, shallow groundwater can be recharged by rainfall infiltration, which is just a part of it. In fact, precipitation falls on the earth and either percolates into the soil or flows across the ground. Usually it does both. The amount of precipitation that infiltrates varies depending on factors such as the amount of water already in the soil, soil composition, vegetation cover and degree of slope. For the arid regions, a large portion will be consumed by evaporation and soil saturation due to little rainfall and deep level of groundwater table, leaving only a little to recharge groundwater.

The precipitation varies from 160 mm to less than 50 mm with the distance away from the costal in Wadi Baye. 90% of the total precipitation concentrates in rainy season (October to March) while the average rainfall in dry season is less than 10 mm even in the coastal area (Figure 3.7). It is concluded therefore that possible infiltration recharge occur only in the middle or downstream of Wadi Baye in rainy season. On the other hand, the depth of water table is usually over 30 m, largely exceeding the limits of evaporation (10 m). That indicates evaporation is hardly involved in regional groundwater circulation. To sum up, shallow unconfined aquifers are recharged by lateral inflows and sporadically by infiltration in the wadi beds when in flow. Besides, upward leakage from the deeper aquifers serves another water The discharge of groundwater contains lateral outflows and exploitation.

For deep confined aquifers, meteorological factors have little effects due to its depth of more than 800 m. Thus, it can be concluded that the main recharge source of deep groundwater is the lateral inflow and its discharges include lateral outflow, exploitation and upward seepage through aquitards into shallow groundwater.

Figure 3.18 represents a conceptual model of the groundwater cycle in the study area. As it just show the “cutting” part of the study area but it’s important to understand that this study area falls into the context of the intra-national-boundary, regional catchment as a “large picture”. Groundwater in this study area may receive recharge from far far south and move slowly toward the Mediterranean.

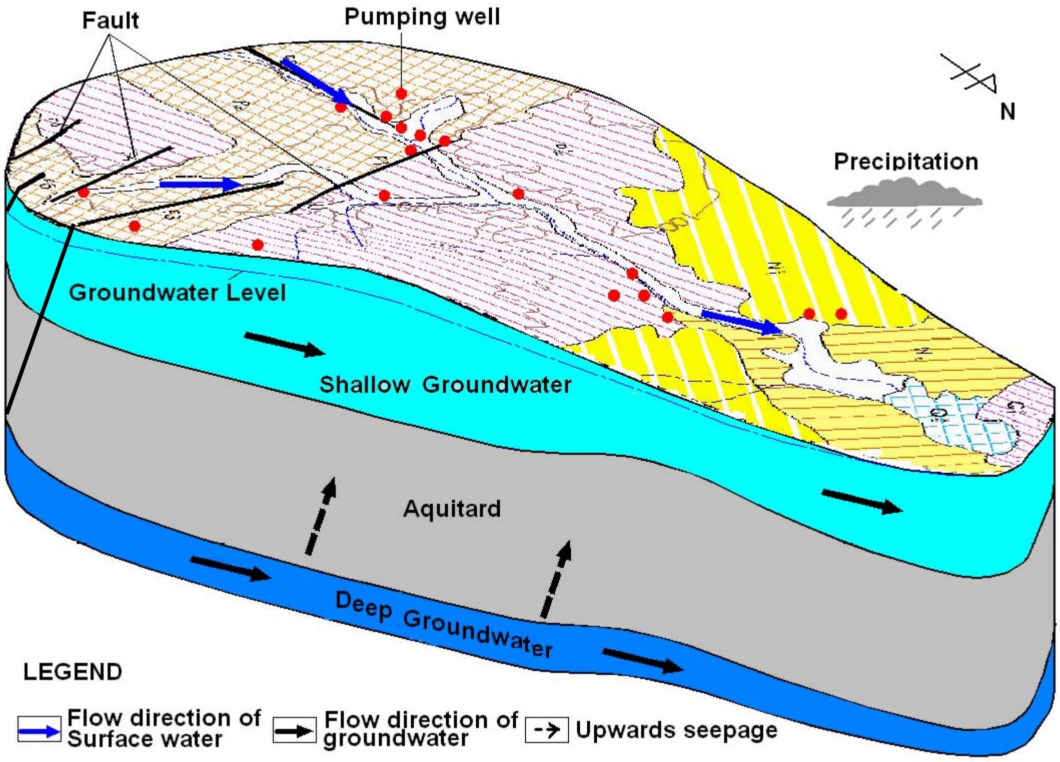

Figure 3.18 The conceptual model of the groundwater cycle in Wadi Baye

Chapter 4 FIELD WORK AND DATA COLLECTION

4.1 Introduction

According to currently activity in Wadi Baye especially in the Agriculture Sector (Ministry of Agriculture) groundwater can be useful for development of this area, as the earliest availability date of the GMRP water is not known to cover the area of Wadi Baye yet. Therefore the case study associated with this PhD project was undertaken on 01 March 2007 to research, collect and collate any available data relating to the Wadi Baye or nearby areas.

Such a field-based survey for groundwater level/ head and hydrochemical and/or isotope sampling would be very useful to provide evidence for wide and further study of groundwater management, e.g. assessment of groundwater quantity and quality of Wadi Baye, and produce useful decision support for management strategy adopted to face to optimised management of the finite available water resource. These will be also important in order to develop/ improve the water uses in this area before future stages. The existing boreholes need to be fully utilised (about 40 shallow and 18 deep boreholes) in Wadi Baye.

This field-based work was based upon extensive desk study investigation done so far including detailed information collected from the Wadi Baye Project Authority, General Water Authority, cities around Wadi Baye authority, baye residents, and authorities of the agriculture projects around this area and Agriculture and Water Ministry. These surveys can be divided into two parts, one is for general information about land use, population, economy and weather information and the other for further significant scientific information includes groundwater measurements, water water quality, water quantity, wells drilling, Wadi Baye plans, rainfall, temperature. Researches have been also done for possible other related information, flooding, irrigation system, environmental and so or. To facilitate the specific groundwater survey, the Wadi Baye investigation was divided into three stages, as illustrated in Figure 2.7, which was attempted to be incorporated into the PhD project.

There are five rounds of field surveys undertaken for the field work and data collection. Each field trip took about one week with great assistance of the Wadi Baye project staff. The field work was carried out at a systematic manner at each site. After locating a well and with the well number on the coding system used by GPS system, the water level/ head measurements were taken and followed by water sample collection at 18 artisan wells for the confined aquifer and 32 sallow wells. The samples were sent to laboratory in the Ministry of Agriculture and Water immediately after returning from the field in each field trip.

- Initial site visit for a walk over survey on 01 to 03 March 2007: checking of the groundwater boreholes, sampling points (ponds, reservoirs etc.), and identification of the location of shallow and deep groundwater boreholes.
- The first sampling trip between 15 to 21 May 2007: GPS survey and mapping for the sampling and measurement locations in the Wadi Baye catchment. The coordinates were calibrated for further mapping, which took long time because of hard topographic area and arrangement of a 4xwheel drive vehicle.

- The second sampling for isotopic analysis in June 2008: It has been a challenging task for isotope analysis as no any facility available in Libya but a great effort has been afforded for this.
- The third trip in July 2009 for general hydrochemical and isotopic analysis and groundwater survey.
- The final sampling in October 2010 for hydrochemical sampling and groundwater level/ head measurement.

The details of the field work and first-hand data collection are described in this chapter, also the laboratory analysis and other issues associated with the field work.

4.2 Groundwater Surveys

Wadi Baye is a dry river with more dry upstream connected and it's the one of the three biggest wadis in Libya (along with Wadi Sof-algin and Wadi Zamzam). It extends from the north to south western roughly with length of more than 500 Km and 2-5 Km wide. Its soil are used as agriculture areas; several Libyan tribes, almost 6000 are living along the wadi with some small villages most of whom are working as a farmers depending upon the rainfall season in most cases rarity. Although artisan wells were available along the wadi but it's difficult to use which need highly technical and government support. The ground surface of the wadi covers with vegetation of rural grass and herb trees which becomes as a suitable area for camels breeding at present. Flooding occurs every 25 years roughly and surface runoff flow from south to north; either wings of the wadi are surrounding with mountains and topographic among plane and hills and some highlands. A general picture of the wadi is shown in Figure 4.1 for the landscape of the study area, which was taken in the March 2007 field trip. Like such a region, travel to the sites of field boreholes, ponds and reservoirs is a problem in the whole campaign of the site visits.

Figure 4.1 Landscape of Wadi Baye (Photo taken in the March 2007 field trip)

The total area in central region about 10,000 km² include many wadis such as Zamzam, Amrah, Zkair, Washka, Aboglop, Omalratm, Abonjeem and the biggest one is Wadi Baye Alkabir. There are about 30 artesian wells and more than 300 shallow wells. Wadi Baye Alkabir covers a total area of 3650 km² and contains 18 deep wells and 53 shallow wells some of the wells are used for several purposes, as showing in table 4.1.

Table 4.1 The monitoring wells in Wadie Baye

Aquifer	Well no	Depth (m)	Yield (m^3/hr)	Tempt. (°C)	formation	strata
Shallow	53	73 to 148	30 to 40	19 to 30	Limestone	unconfined
Deep	18	1210 to 1574	170 to 300	65 to 70	Sandstone	confined

The shallow well (Nos. 1 -40) and 18 deep well are distributed at different locations along Wadi Baye. The locations of the sampling points for both shallow and deep aquifer systems are also presented in Figure 4.2.

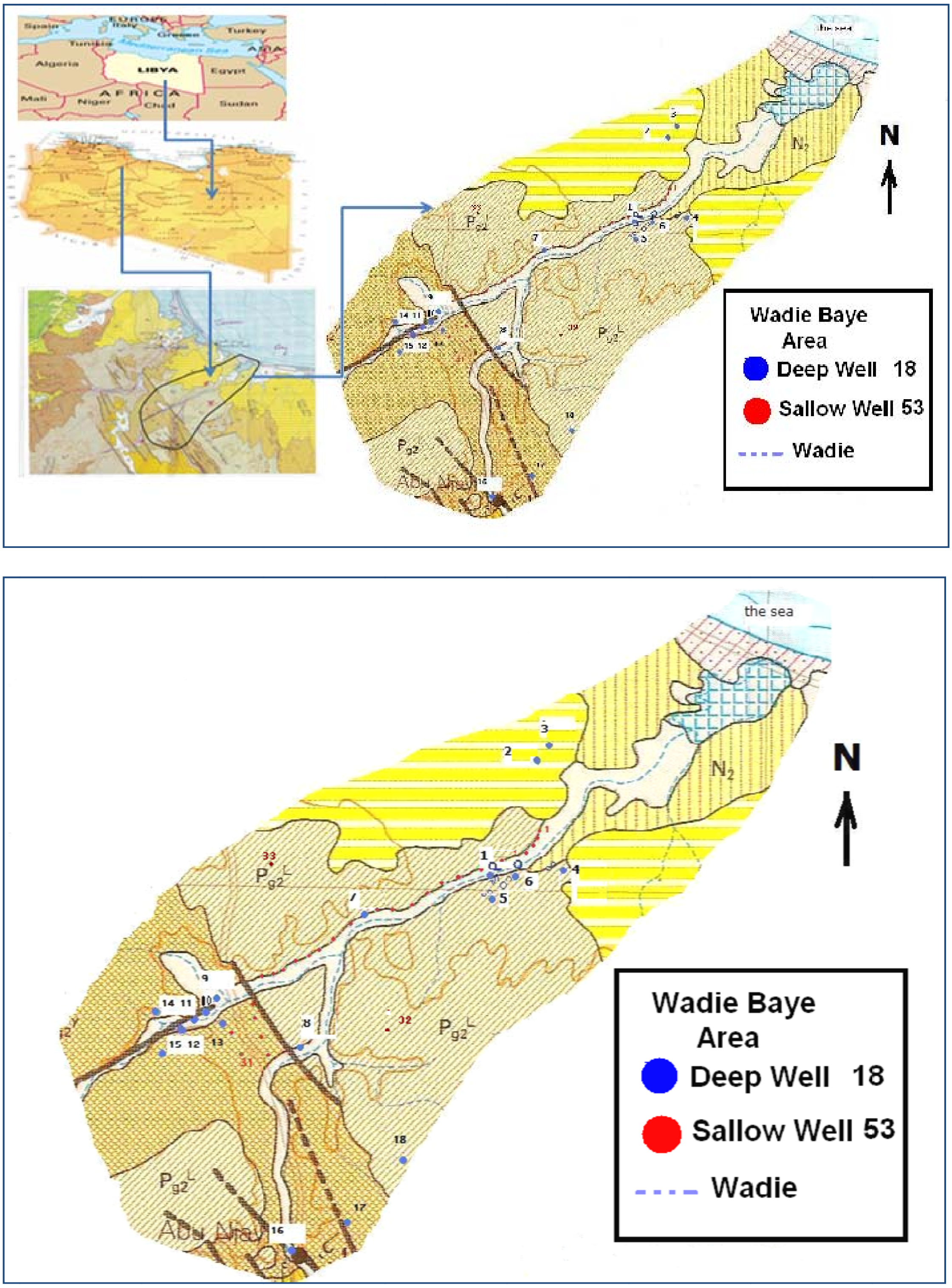

Figure 4.2 Location of the deep and shallow wells in Wadi Baye

There are three aquifer systems in the study area that provides groundwater to the central region and the Wadi Baye project as illustrated in the previous Chapter, a) Eocene limestones/ dolomites (Tertiary age); b) Gharian or Nalut Dolomite (Upper Cretaceous age); c) Kikla Sandstones (Lower Cretaceous age). In our actual investigations, the systems are considered as an unconfined aquifer and a confined deep aquifer for simplicity and practical reason.

4.2.1 Shallow groundwater

According to the previous geology investigations, shallow groundwater has been inferred as the Tertiary age Eocene limestone/ dolomites, unconfined with groundwater levels below ground surface in Libya central region and the Wadi Baye area. The administration of the Wadi Baye project has drilled 40 shallow wells through the years 2003-2006 in accordance with the technical specifications from the Agriculture Development Organization in Libya. These have been planned to design the best water management strategy in the Wadi Baye area, with wells depths between 73 - 148 m (see Table 4.1), installed with submersible pumps for production. They normally yield between 30 - 40 m^3/hr.

It is normally possible for groundwater level dipping, see Figure 4.3, directly for most of the shallow wells. However, a few wells have to be helped with the staff of Agriculture and Water Ministry for access.

Figure 4.3 Shallow well with a tape dip-meter (a) and sample collection in 2008 (b)

In this study, shallow groundwater would be taken into account as another alternative source for water supply in Wadi Baye to meet the demands of the proposed suitable supply for human and agricultural purposes. Hence the investigations and field work been done in this study to consider to be able to serve the future groundwater modelling and management plans.

4.2.2 Deep artesian groundwater

Current stage, the only potential is from the Kikla Sandstones which is used though to a much less extent than in the past for the existing agricultural projects: Wadi Zamzam and Wadi Wishkah. The eighteen Wadi Baye Project wells (Nos. 1 to 18) are completed in the Kikla aquifer, and four wells (1, 4, 5 and 6) are playing a basic role as a water source in Wadi Baye project to provide water for irrigation and other purposes. All groundwater production has been from naturally overflowing wells – the Kikla is a confined aquifer with groundwater levels above ground surface at various extents.

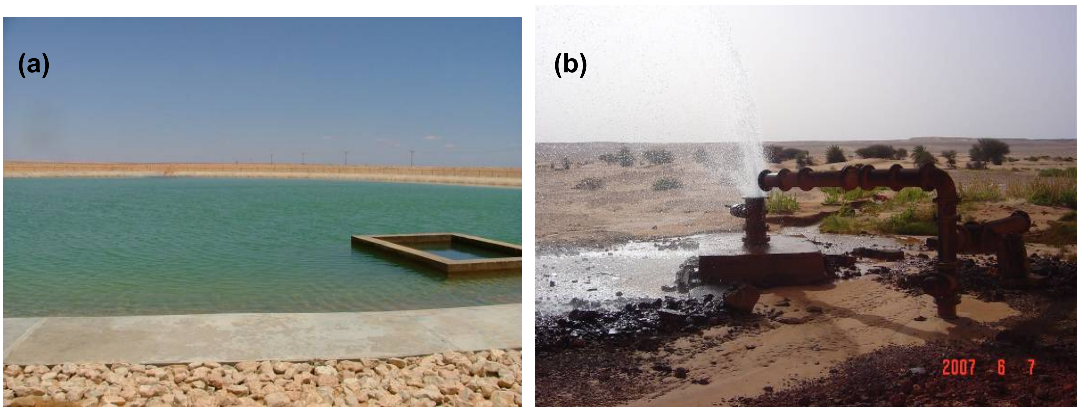

Figure 4.4 Pond of 8000 m^3 close to deep well (a) and a deep overflowing well (b)

As a result of groundwater production, artesian groundwater levels have fallen since the mid 1970s by approximately 60 m in Wadis Zamzam and Wishkah and in the northernmost project wells in Wadi Marah (Nos 2 and 3). Yield from well No. 2 is almost nil and it is not at this time considered a viable source for the project. The decline has been somewhat less, in the region of 30 to 40 m, in the area of the remaining Wadi Baye wells (Nos. 1, 4, 5 and 6).

Wadi Baye, as an agricultural region, has occurred groundwater level declines due to the increasing irrigation water use supplied by groundwater. Relevant data indicated ground water levels for Kikla aquifer had declined by 35 m in the two decades from 1970s to 1980s at an average rate of 1.75 m per year with the total water storage decreasing by 260 million m^3. Till 2009, depression cones has formed near 3 pumping wells (1$^\#$, 5$^\#$, 6$^\#$) as shown in Figure 4.5, according to our groundwater survey. The water was mainly consumed by agricultural irrigation at 85%, followed by domestic and industrial use at 11.5% and 3.5% respectively.

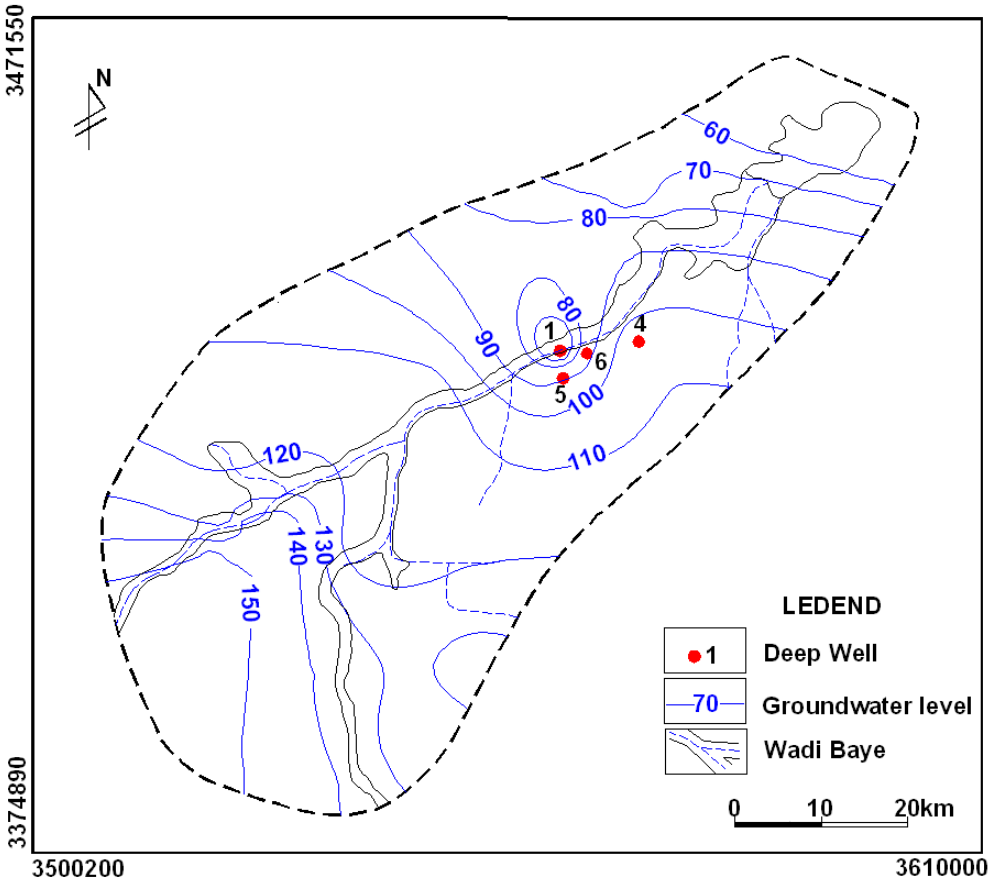

Figure 4.5 Contour of deep groundwater level in Febuary 2009

The deep well performance of such that a total estimated yield of 255 L/s is available from the four project wells in Wadi Baye. There is some minor variation between wells but no variation with flow rate or season at a single well. The maximum measured water temperature of the groundwater is 73. It is so hot that the pond system (deep wells, pipelines and eight cooling ponds and two reservoirs) has to be incorporated (see previous Chapter) before the deep water can be used for irrigation or other purposes, to drop down the temperature at about 40°C. The engineering design parameters of the cooling ponds were based on the findings of the thermodynamic modelling study done by Halcrow but not too much relevant to this study.

4.2.3 Additional field work

To make the study complete several visits have been taken to the meteorological stations and then climate data for more than 20 years were collected including (temperature, rainfall, humidity, evaporation, solar brightness etc.). Some problems were faced because no observation station in the study area so all weather information obtained from Sirt, Abounjeem, Musrata and Hun Stations, which were used for our study with proper reference.

In addition some samples had been taken from the sea and rainfall for isotope analysis and the analysis results were taken into a count through the study.

After some modelling exercise, it has been found that the modelled flow and hydrochemical data could not completely agree. Therefore additional (final) field trip was undertaken on 2nd October 2010 with results received 24 November 2010 and with assistance by the staff of the Laboratory at the General Water Authority- Tripoli. These were chemical analyses to determine the concentration of the major ions: Sodium, Potassium, Calcium, Magnesium, Chloride, Bicarbonate/ Carbonate and Sulphate, NO_3, NH_4 and the others (Sr, Mn, Si, Ba) same to previous campaigns. The electrical conductivity, total dissolved solids, pH and Alkalinity (in CaCO3 mg/l**)** were also measured.

4.3 Laboratory analysis

4.3.1 Radiation analysis

Radiation analysis was carried out using the samples collected in May 2007 by a private laboratory in Tripoli**.** With assistance by the staff of the Laboratory, all the samples brought from the field were subjected to partial radiation analysis. These radiation analyses were aimed to determine the concentration of the existing external gamma, alpha and beta radiation in the Wadi Baye groundwater samples. The result obtained showed no signatures of those radiation. It's a peace of mind in the end but this analysis has been done with high price.

A background radiation measurement were taken from the working environment and left for a period of fifteen minutes. The γ-radiation in the background was found to be in the range of 15~18 nSv/h, whilst the α- and β- radiations were found to be in the range of 0.03~1 cpm. Note that the background radiation may reach to 30~35 nSv/h level some occasions.

As received each sample of one litter approximately was poured into a special tray which is completely fit to the instrument that will be used for the radiation detection. The dose-rate measurements from radiation survey were taken according to the number and notes on the containers. These measurements were conducted exactly on the surface of the water samples for a period of three minutes by using these two instruments:

- Mini Spec NaI and GM for γ-radiation,
- Contamination Monitor LB 124 for α- and β-radiations.

4.3.2 Hydrchemical analysis

The general hydrochemical analysis was carried out for the samples collected on 14 July 2009 by the General Water Authority Laboratory, Tripoli, with assistance of the staff of the laboratory. The result was received on 18 November 2009.

All the samples brought from the field were subjected to chemical analysis, aimed to determine the concentration of the following ionized elements: Sodium (Na^{+}), Potassium (K^{+}), Calcium (Ca^{+2}), Magnesium (Mg^{+2}), Chloride (Cl), Bicarbonate (HCO_3^{-}), Carbonate (CO_3^{-2}), Sulphate ($S04^{-2}$), NO_3, NH_4 and others minor ions Sr, Mn, Si, Ba.

In addition to the cation and anion determination, the electrical conductivity (EC), the total dissolved solids (TDS), pH and the Alkalinity (CaCO3 mg/l**)** have been measured. Doubled check measurements of borehole depth (m), groundwater depth below ground (m), and converted groundwater elevation from the Sea Level (m) and water temperature *T* (°C) have also been taken at the site during field work. The data have been handled and interpreted in the following Chapter to understand groundwater salinasation, general hydrogeochemical evolution of groundwater.

4.3.3 Isotope analysis

Isotopes analysis can be costly, complicated but unfortunately no any facility in Libya so far. It has been taken a long time, needing a lot quantity of water samples and chemical materials. It was only determined after travelling three times to Tunisia that this type of analysis can be done as no chance to do this back to the UK, too expensive for the sampling handling. The first effort to do isotope analysis was sadly not done in June 2008 due to nowhere for analysis – wasted two months time for field sampling and preparation. It took almost three months from 12 August 2009 until 13 November/ 2009 before the final result was received.

A regards of the steps of isotope analysis to determine the concentration of the Oxygen (O^{18}), Tritium (H^{3}), deuterium (H^{2}) and Carbon (C^{14}), which can be some Figs (4.6, 4.7 and 4.8) for illustrating of them:

- 51 Samples been collected (shallow and deep groundwater) were taken to Laboratoire de Radio-Analyses et Environnement Ecole Nationale d'Ingénieurs Engineering School – Sfax – Tunisia for Tritium (^{3}H) and deuterium (^{2}H);
- To determine the alkalinity in order to know the quantity of water need for each sample and so some samples needed 80L, 60L and even 140L; and the total quantity was more than 3500L was so difficult to carry to Tunisia

Figure 4.6 Water quantity of samples at the site (A) and sodium chloride (B)

Figure 4.7 Barium chloride (A) to be add to form the CITD precipitate (B)

Figure 4.8   The samples before CITD (a) and pH paper (b)

As the above reason some part of steps were done in the field in Wadi Baye fallowing Protocol for precipitation of CITD as to**:**

Reduce the pH to 12 by adding sodium chloride (checked with pH paper).

Add barium chloride (4 to 5 g/L), wait a few hours so that the precipitate forms and falls toward the bottom of the can.

Throw the float (clear water) and keep the CIDT, once the precipitate (CITD) is settled to the bottom (very careful not to lose any ICSD).

Transfer finally the CITD in another little bottle.

4.4   Summary

It has been problem in Wadi Bay, Libya to carry out such groundwater survey in the field. It has been some stressful time but all problems had been solved with satisfactory results from the field work and all elements of the data collection work.

It has been suggested to carry out regular sampling and analysis for groundwater flow field and quality monitoring but due to lack of funding and systematic approach for the field study. It is still not possible to get any further done so far beyond this PhD project.

The data collected from the field and all other sources would be a fundamental part of this research that is from this a bit by bit field effort, from groundwater level survey to sampling and further isotope analysis. ? comprehensive hydrogeological work was done in the Wadi Baye area.

Chapter 5 GROUNDWATER QUALITY AND HYDROGEOCHEMICAL EVOLUTION

5.1 Introduction

Groundwater resource is the main source of freshwater in Wadi Baye. However, groundwater exploitation in the region has increased dramatically during the last decades, mainly due to an increase in agriculture, tourism and industry (EMWIS, 2005). This phenomenon has a marked impact on depletion of groundwater quantity as well as deterioration in quality.

In this study, groundwater samples were collected from 30 shallow wells and 18 deep wells in Wadi Bay. The distributions of sampling wells are shown in Figure 5.1 and Figure 5.2. In order to evaluate the groundwater quality and its hydrochemical evolution, measurements of the chemical compositions of groundwater were carried out, such as CO_3^{2-}, HCO_3^-, Cl^-, Ca_2^+, K^+, Mg_2^+, Na^+, SO_4^{2-}, pH, EC, temperature . Moreover, samples were collected from all the 48 monitoring wells for hydrogen, oxygen stable isotope and Carbon-14 radioactive analyses as mentioned in Chapter 4.

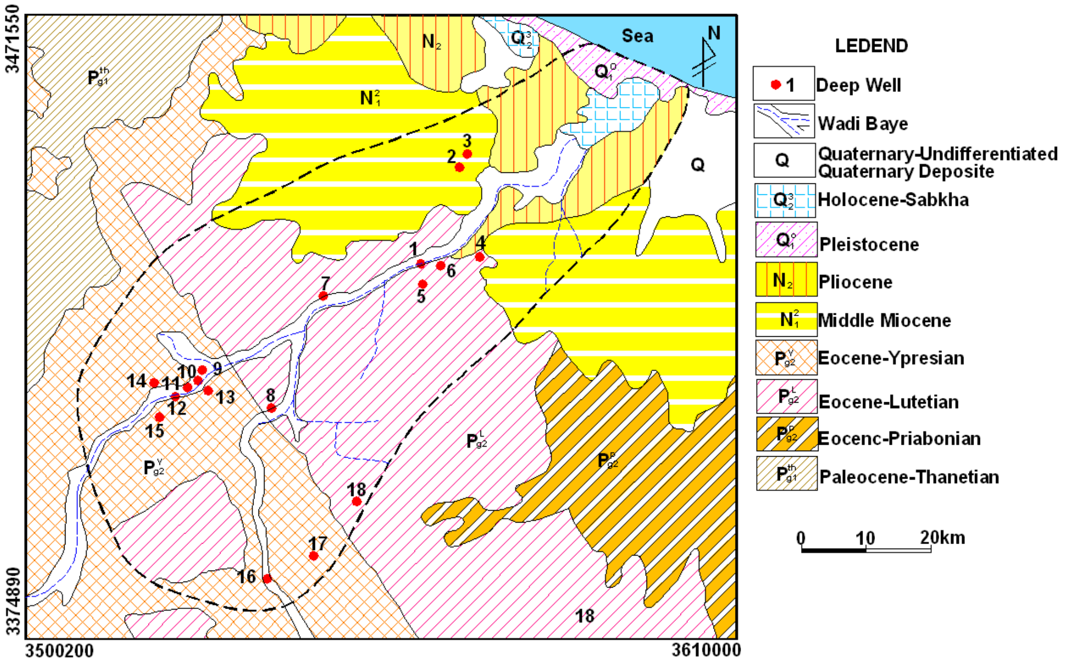

Figure 5.1 Distribution of sampling wells for deep aquifer

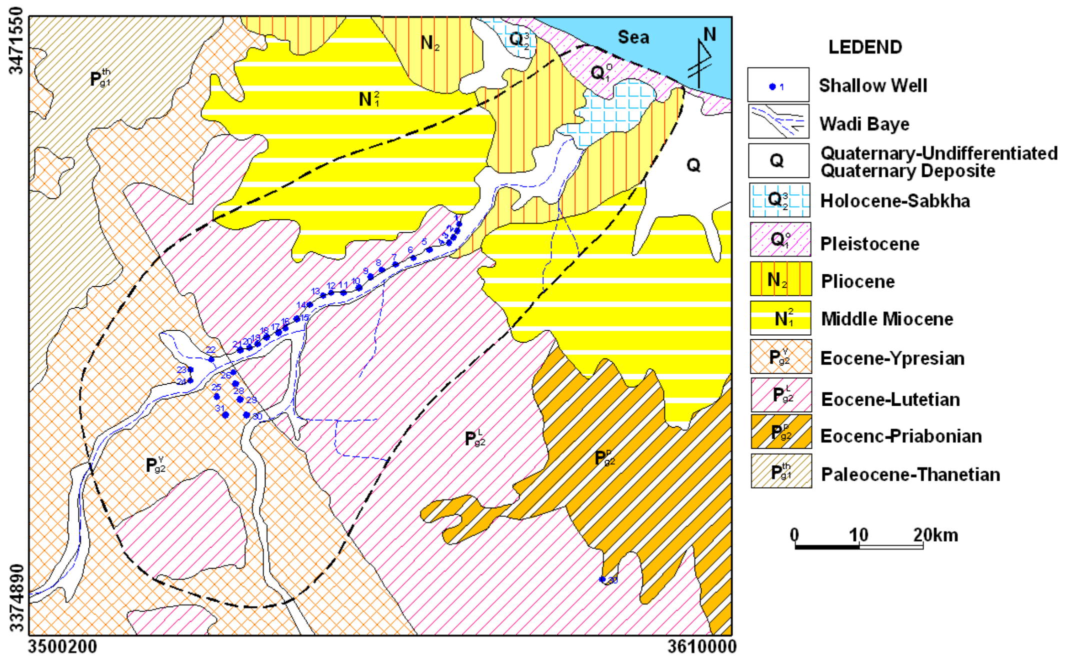

Figure 5.2 Distribution of sampling wells for shallow aquifer

5.2 Hydrochemical Characteristics of Groundwater

Table 5.1 summaries the range of groundwater chemical parameters for two aquifers in Wadi Baye. In general, TDS in groundwater is a little higher, especially in shallow groundwater. The pH values were found to be in the range of 7.0 - 8.0, neutral to alkaline range. The hardness is high at more than 180 mg $CaCO_3$/L, ranked as extremely hard water. Comparison of chemical components between the two groundwater systems shows concentrations of most ions in shallow groundwater are higher than that in deep groundwater except K^+ and HCO_3^-, indicating deep groundwater is better than shallow water in quality.

Table 5.1 Summary of shallow and deep hydrochemistry in Wadi Baye

	Shallow groundwater			Deep groundwater		
	Maximum	**Minimum**	**Average**	**Maximum**	**Minimum**	**Average**
pH	7.69	7.05	7.23	7.35	7.01	7.21
TDS(mg/l)	8368.52	3209.49	5578.33	2700.86	1451.50	1700.86
Hardness (mg $CaCO_3$/l)	3017.58	1300.41	2162.53	840.29	500.18	598.75
Na^+(mg/l)	1760.00	507.50	1154.23	508.00	236.00	288.44
K^+(mg/l)	72.00	53.00	63.53	120.00	48.00	65.78
Ca^{2+}(mg/l)	670.20	320.08	501.03	216.05	96.02	129.43
Mg^{2+}(mg/l)	331.95	115.25	218.39	86.44	28.81	66.04.
HCO_3^-(mg/l)	331.95	214.70	244.42	468.63	253.84	304.59
Cl^-(mg/l)	2975.00	823.40	1802.06	684.61	399.88	503.77
SO_4^{2-}(mg/l)	2392.00	923.00	1587.47	658.52	260.12	339.38

In addition, the proportion of major ions in shallow and deep groundwater is presented in Figure 5.3 and Figure 5.4. From these two pie charts, it can be seen that Na^+ and Cl^- are the prevalent cation and anion. The relative abundance of the cations is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, and that of the anion is $Cl^- > SO_4^{2-} > HCO_3^-$ for shallow groundwater and $Cl^- > HCO_3^- > SO_4^{2-}$ for deep groundwater.

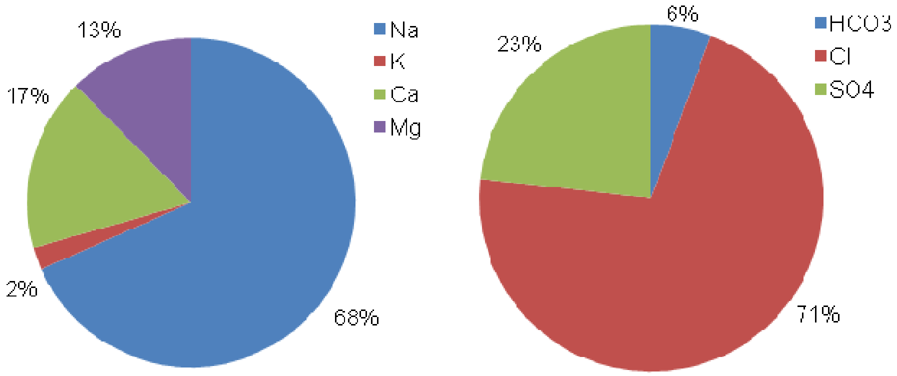

Figure 5.3 Proportions of major ions as meq/L in shallow groundwater

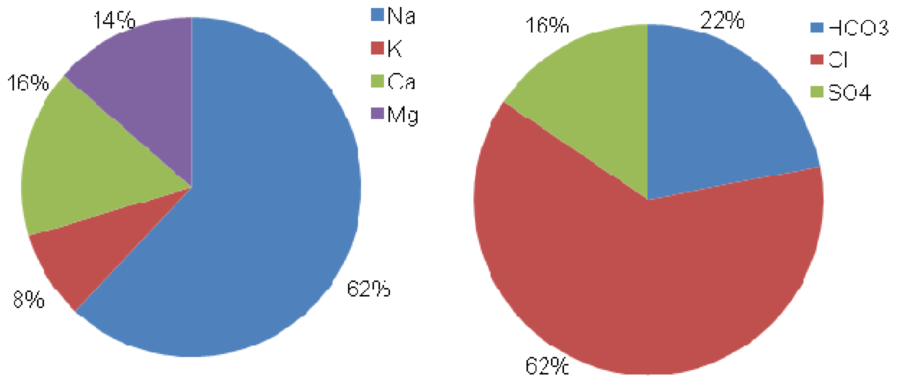

Figure 5.4 Proportions of major ions as meq/L in deep groundwater

5.3 Total dissolved solid and Hydrochemical type of Groundwater

5.3.1 Total dissolved solid (TDS)

Total Dissolved Solids (TDS) is a measure of the combined content of all inorganic and organic substances contained in a liquid in: molecular, ionized or micro-granular (colloidal solids) suspended form. The principal application of TDS is in the study of water quality, although TDS is not generally considered a primary pollutant it is used as an indication of aesthetic characteristics of drinking water and as an aggregate indicator of the presence of a broad array of chemical contaminants.

According to TDS in water, groundwater is classified as fresh water (TDS<2.5g/L), slight saline water (2.5g/L<TDS<5g/L) and saline water (TDS>5g/L) in Groundwater Standard of Libya (Viena, Austria, 2006.).

1) Shallow groundwater

The TDS of shallow groundwater in the study area ranges between the 3201 and 8369 mg/l, identified as salty water. From the TDS contour map of shallow groundwater (Figure 5.5) we can see that TDS increases dramatically from the Wadi Bay upstream to downstream by 5500 mg/l.

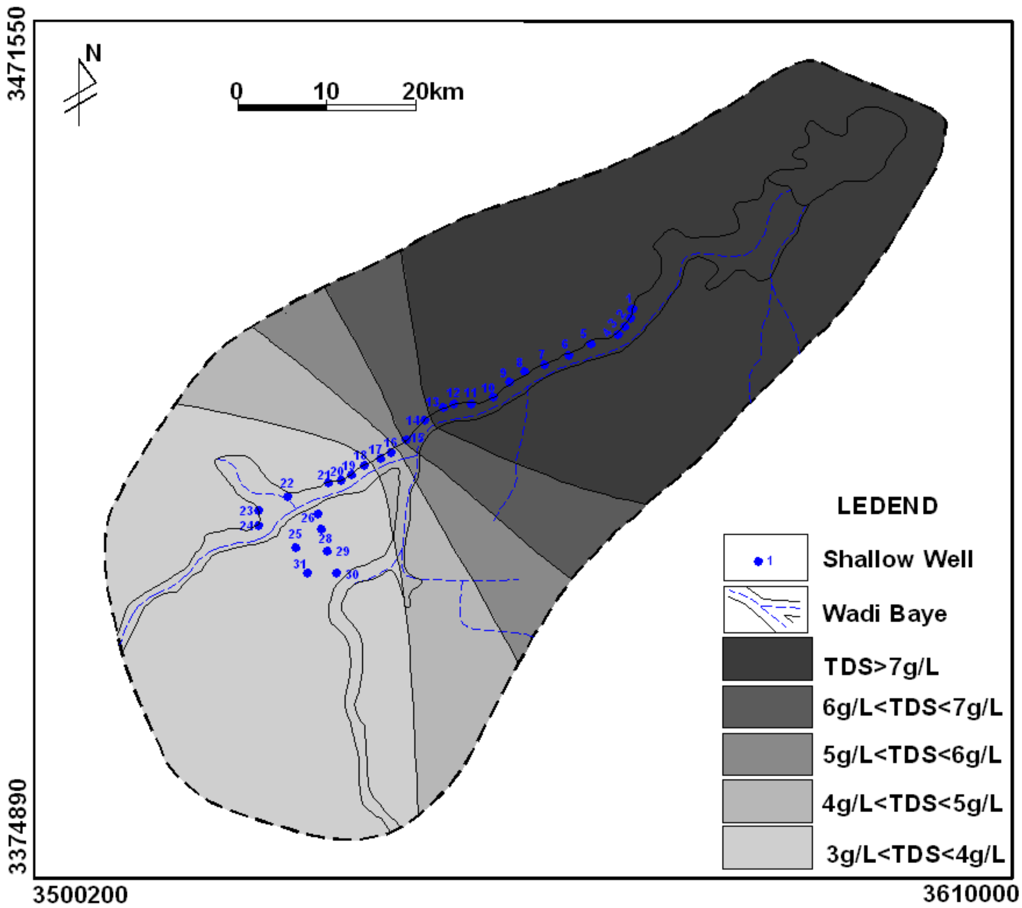

Figure 5.5 TDS contour of shallow groundwater

2) Deep groundwater

Compared with shallow groundwater, The TDS of most samples in deep wells is much lower in the range of 1 - 2.5 g/L except the wells of 3 and 4, which is slight saline water. From Figure 5.6, it is obvious that TDS also increases from inland to coast, which may be caused by water-rock interaction or ancient saline conditions.

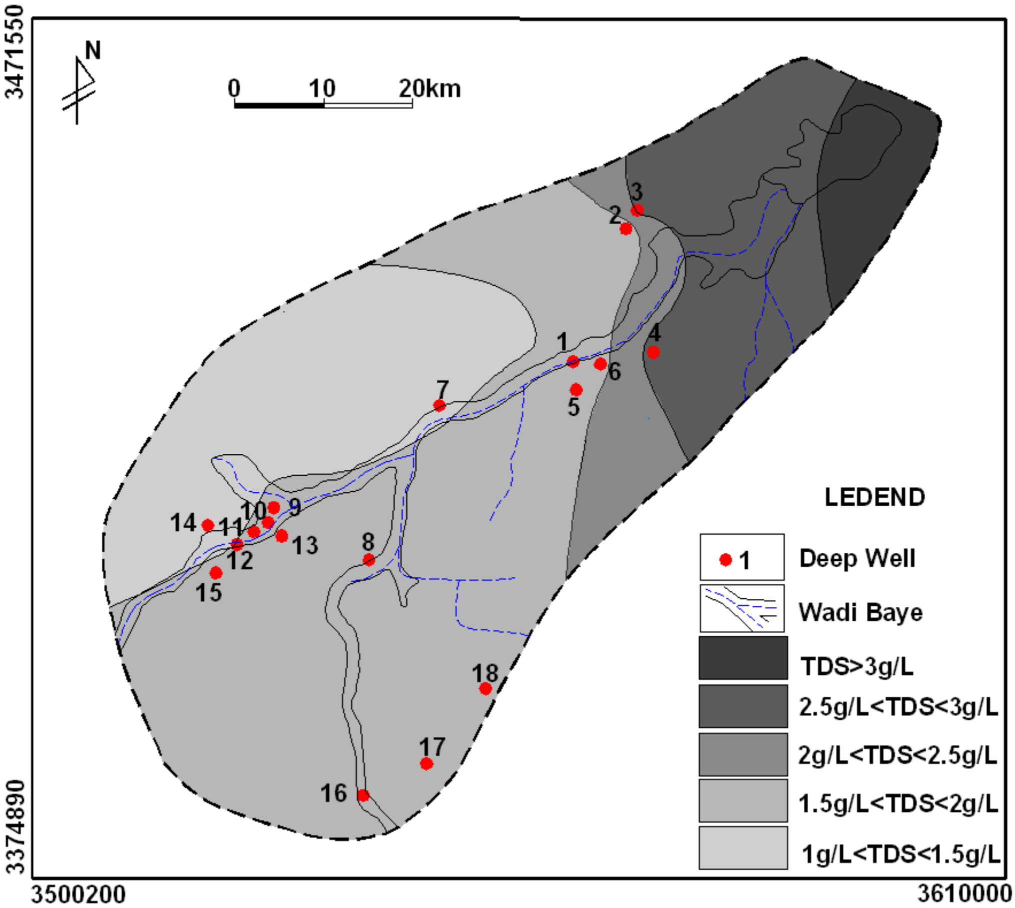

Figure 5.6 TDS contour of deep groundwater

5.3.2 Hydrochemical types of groundwater

The Piper diagram is a graphical representation of chemistry of a water sample or samples. It is composed by three parts as two trilines and one diamond. The cations and anions are shown by the separate triangles. The apexes of the cation plot are calcium, magnesium and sodium plus potassium cations. The apexes of the anion plot are sulphate, chloride and carbonate plus hydrogen carbonate anions. The two ternary plots are then projected onto a diamond. The diamond is a matrix transformation of a graph of the anions (sulfate + chloride/ total anions) and cations (sodium + potassium/total cations). To reflect more information on this diagram, the relative TDS content can be described by the size of symbol among more than two samples. This study introduced Piper diagrams to interpret the hydrochemical evolutions for different groundwater systems using the software program AquaChem.

1) Shallow groundwater

According to the hydro-chemical data of shallow groundwater samples, a Piper diagram was drawn and shown in Figure 5.9. Samples are concentrated in the ? zone of the anions, and alkali metal zone of the cations. The groundwater types divided according to the Piper classification are $Cl\cdot SO_4$-$Na\cdot Ca$ and $Cl\cdot SO_4$-Na. Combined information with the given by Figure 5.5 and Figure 5.8, a general rule in this area can be drawn that groundwater with TDS less than 4 g/L is $Cl\cdot SO_4$-$Na\cdot Ca$ solution, while that with TDS more than 6 g/L is $Cl\cdot SO_4$-Na.

3) Deep groundwater

As shown in Figure 5.9, Samples of deep groundwater are also ? of the anions, anions, and alkali metal zone of the cations, which indicates the proportions of HCO_3^-, Ca^{2+}, Mg^{2+} are less. There are five type solutions, that being $Cl\cdot SO_4$-Na, Cl-Na, $Cl\cdot SO_4$-$Na\cdot Ca$ and Cl-$Na\cdot Ca$. Figure 5.10 indicates the former type solutions occupies most of the area in Wadi Baye, and solution type has very close relationship with TDS in water.

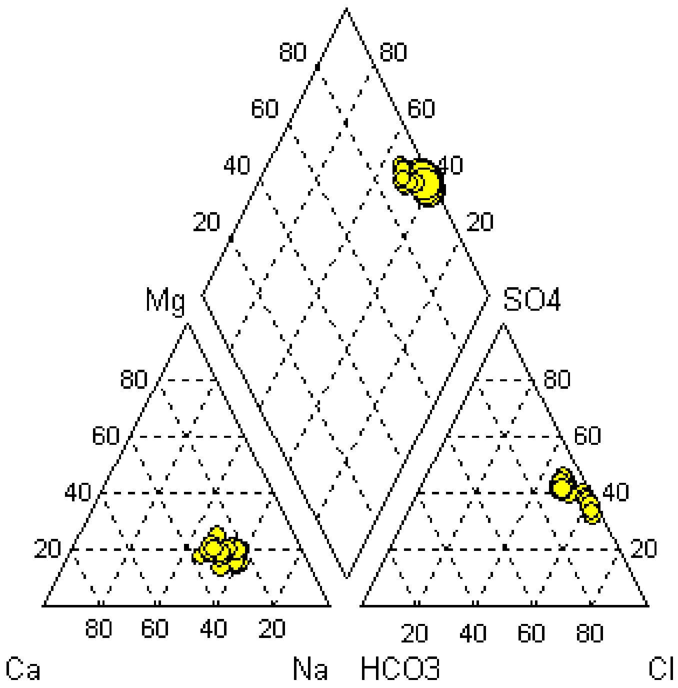

Figure 5.7 Piper diagram of shallow groundwater

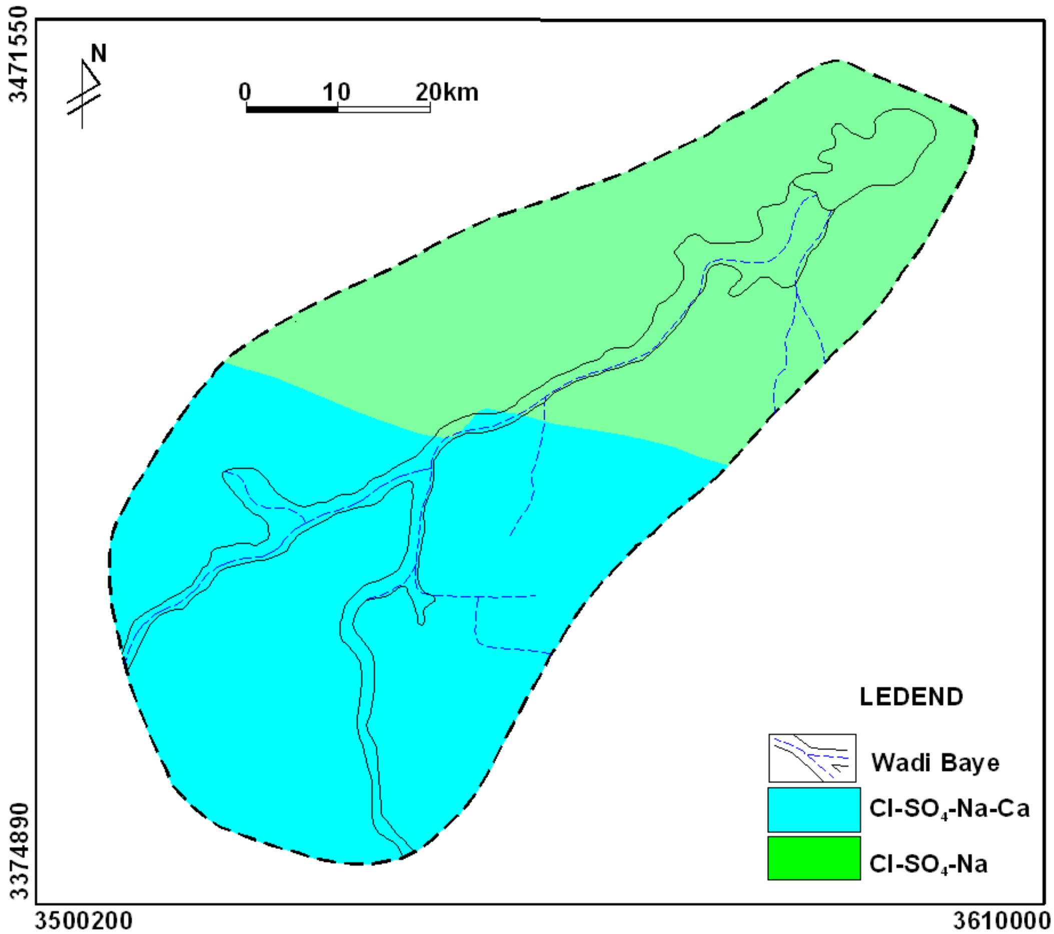

Figure 5.8 Distribution of groundwater types for shallow aquifer

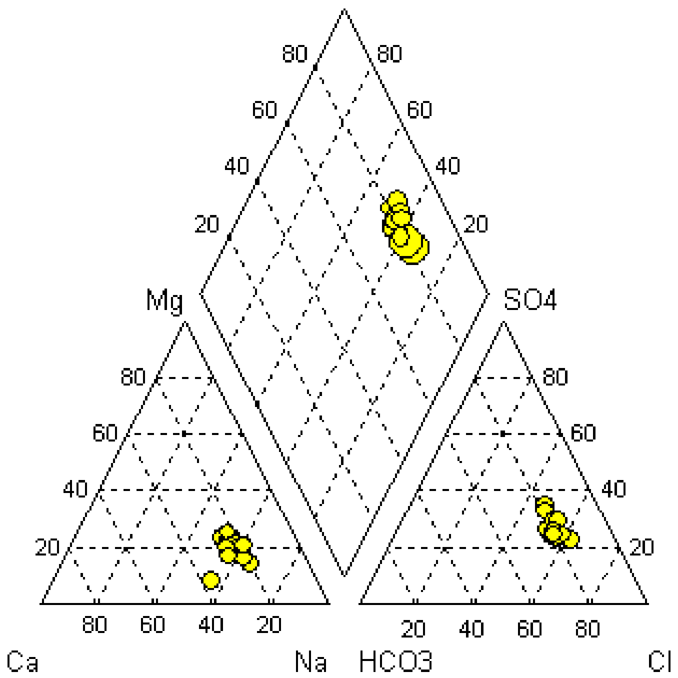

Figure 5.9 Piper diagram of deep groundwater

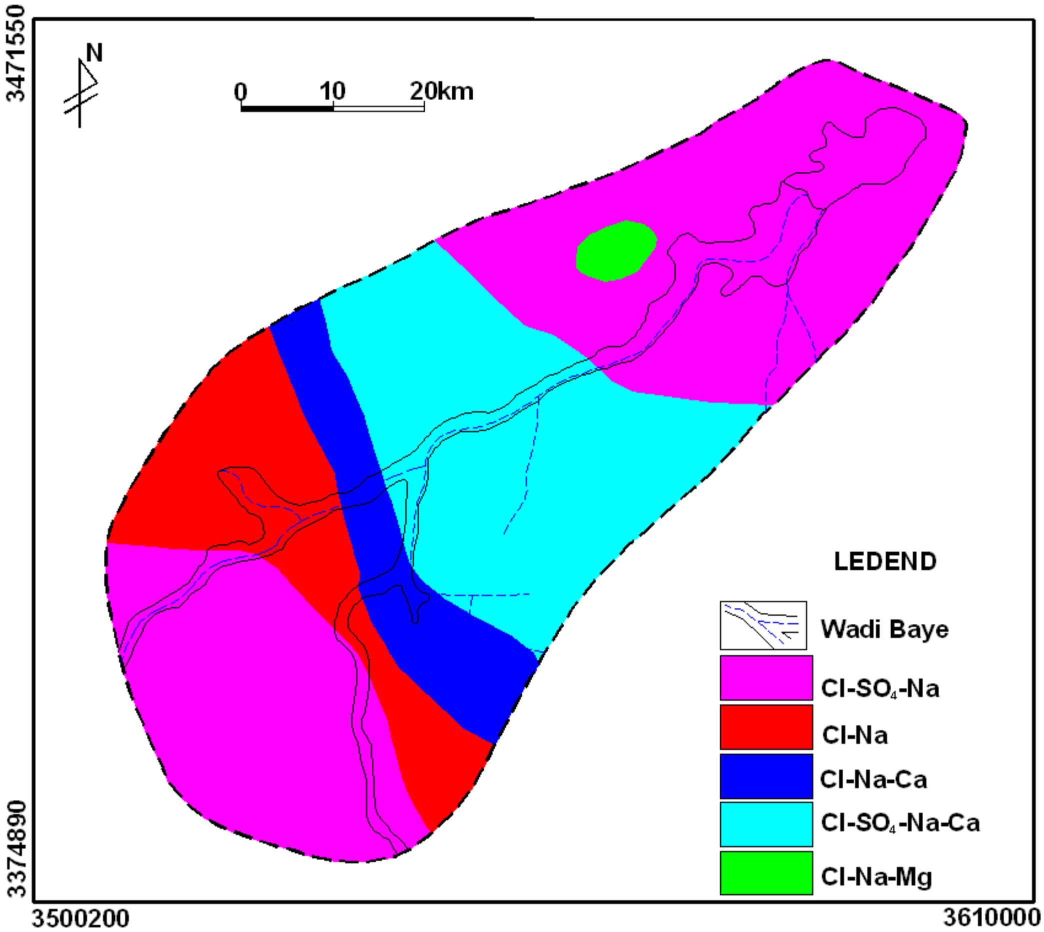

Figure 5.10 Distribution of groundwater type for deep aquifer

5.4 Spatial Variation of Groundwater Chemical Composition

5.4.1 Shallow groundwater

Taking into account the nearly "linear" distribution of the shallow wells in the direction of groundwater flow, the spatial variation of hydro-chemical characteristics then can be analyzed along the groundwater flow, namely the direction from inland to the sea.

According to Figure 5.11, variations of concentrations of Cl^-, Na^+, SO_4^{2-} are in a good phase with that of TDS along the flow path. Generally, ion concentrations of groundwater in the south are much lower than that in the downstream of discharge region, and a dramatic fall occurs at the point of 70 km from the coast. TDS slumps from 7044 mg/L to 3491 mg/L and the concentration of Cl^- fells down to 978 mg/L from 2432 mg/L at that point. Similarly but not sharply, concentrations of Ca^{2+} and Mg^{2+} decrease from 550 mg/L to 400 mg/L and 300 mg/L to 200 mg/L respectively (Figure 5.12). Additionally, several minor components such as Mn^{2+}, Ba^{2+} and Si^{2+} fluctuated along the flow path with no obvious increase or decline (Figure 5.13).

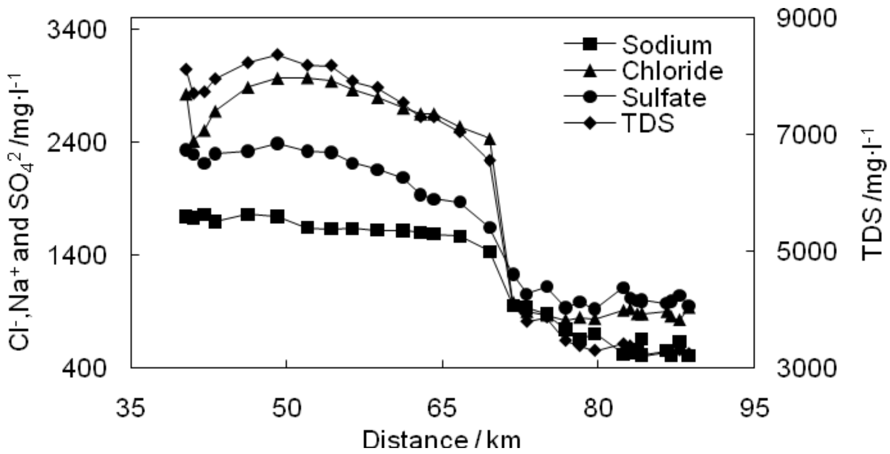

Figure 5.11 Variation of TDS, Cl^-, Na^+ and SO_4^{2-} with distance from the sea

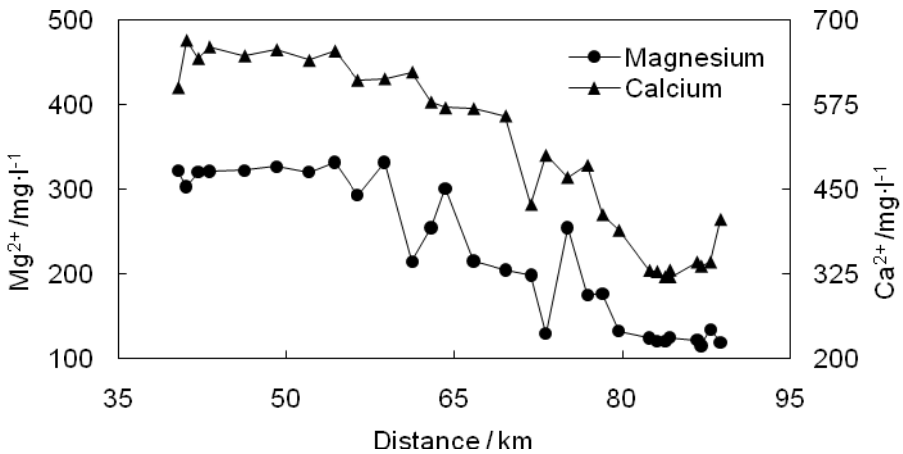

Figure 5.12 Variation of Ca^{2+} and Mg^{2+} with distance from the sea

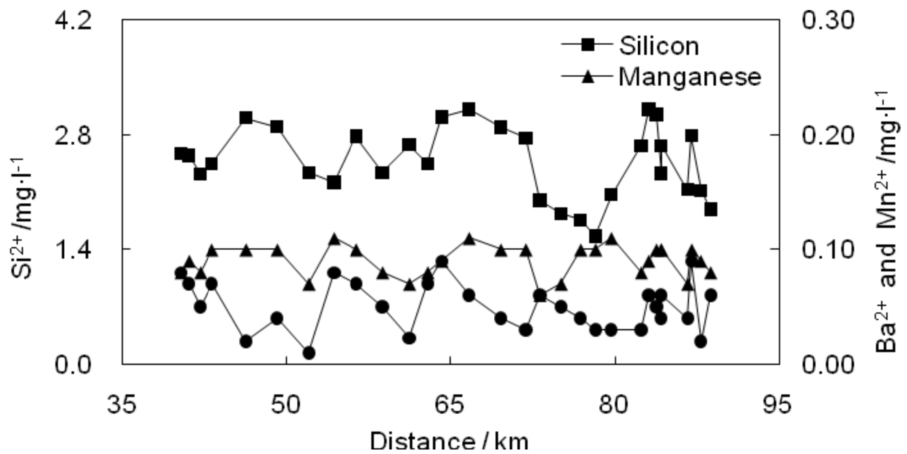

Figure 5.13 Variation of Mn^{2+}, Ba^{2+} and Si^{2+} with distance from the sea

5.4.2 Deep groundwater

The characteristics of TDS and major ions in deep groundwater present the same variation trend as the shallow groundwater, but the break point is much closer to the sea, just between 50 km and 55 km from the coast (Figure 5.14 and Figure 5.15).

From the break point to the inland, the concentrations remain stable at low values. The minor components such as Mn^{2+}, Ba^{2+} and Si^{2+} have no obvious increase or decline either (Figure 5.16).

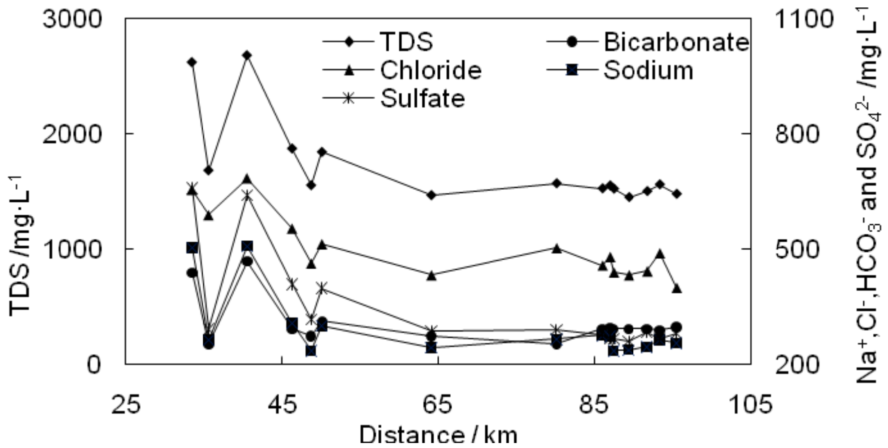

Figure 5.14 Variation of TDS, Cl^-, Na^+ and SO_4^{2-} with distance from the sea

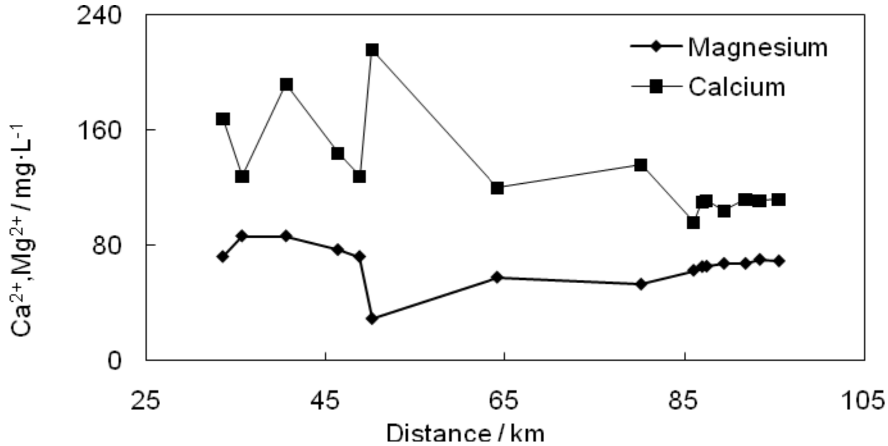

Figure 5.15 Variation of Ca^{2+} and Mg^{2+} with distance from the sea

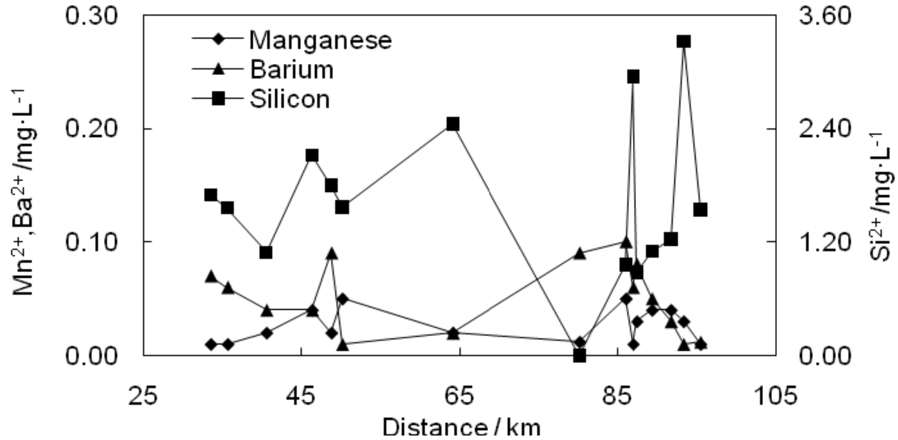

Figure 5.16 Variation of Mn^{2+}, $Ba^{2+}$and Si^{2+} with distance from the sea

5.5 Isotopic characteristics of groundwater

5.5.1 Oxygen and Hydrogen isotopes

The isotopic signature of the shallow groundwater and deep groundwater are significantly different (Figure 5.17). The δD and $\delta^{18}O$ of the shallow groundwater are in the range of -65.03~-58.35‰ and -9.96~-7.48‰ respectively versus V-SMOW, whereas the deep groundwater signature is lower with δD ranging from -74.40‰ to -64.91‰ and $\delta^{18}O$ from -10.39‰ to -8.33‰. Besides, either shallow groundwater or deep groundwater, points in Figure 5.17 are obviously divided into two parts which is possibly controlled by some factors such as recharge source, flowpath and discharge way, and even interactions between groundwater and surface water.

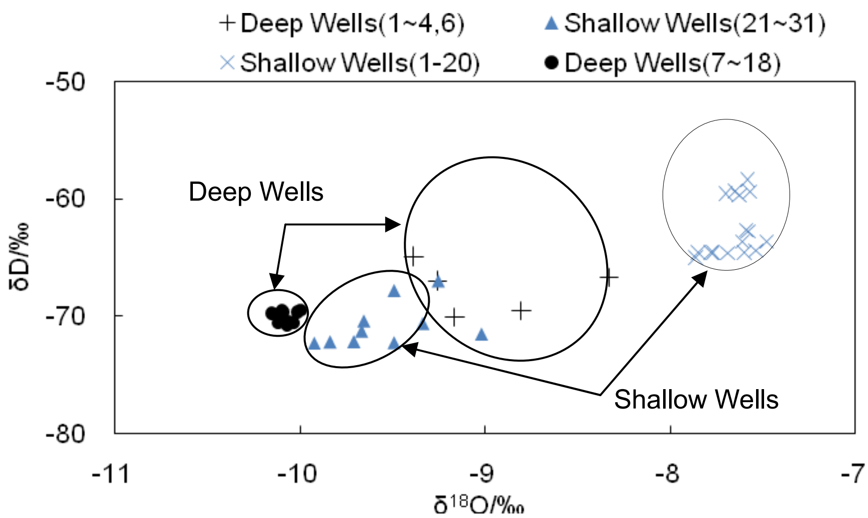

Figure 5.17 Relationship between $\delta^{18}O$ and δD of groundwater in Wadi Baye

The $\delta^{18}O$ and $\delta^{2}H$ values of the shallow aquifer samples are depleted and more homogeneous than the values measured in the deep aquifer. The most enriched values are recorded in wells No. R1, 116, 112 and 120 and the dug well 127. However, the most depleted values are recorded in the deepest part of the aquifer, with $\delta^{18}O$ values range between –10.4 and –9‰ vs SMOW.

The $\delta^{18}O/\delta^{2}H$ diagram shows that the groundwater samples plot below the GMWL, except three points (wells 103, 139, 140, 150, 152 and 153) which plot along this line. Groundwaters from the referred wells, which are collected in the deep aquifer, are probably mixed with recent recharged water. The other samples are characterized by an evaporation effect as shown by their positions below the Global Meteoric Water Line. The relationship is presented in Figure 5.18 below.

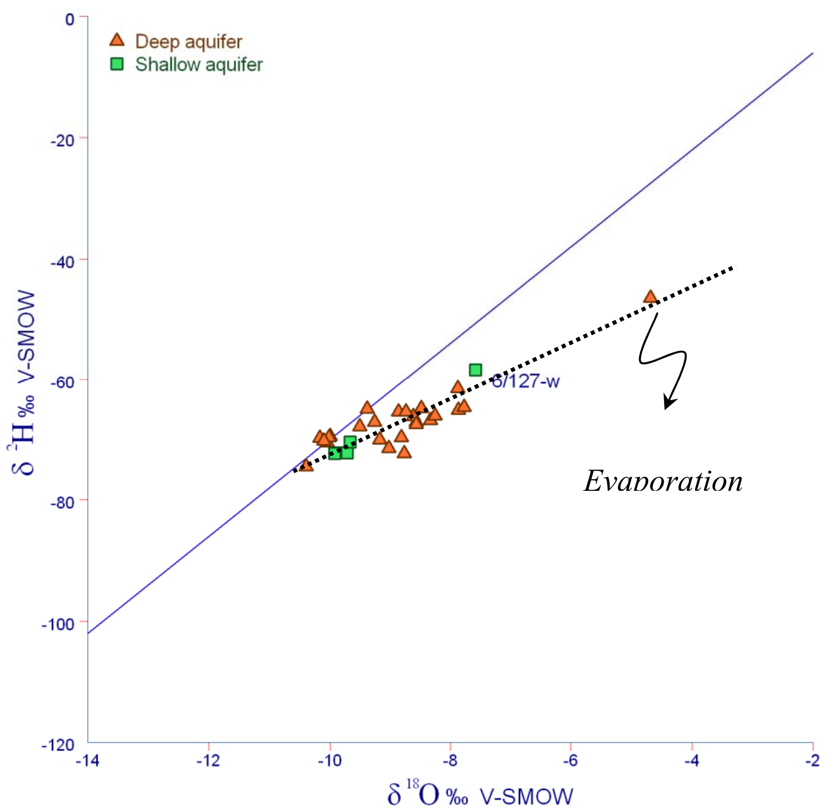

Figure 5.18 Relationship between $\delta^{18}O$ and $\delta^{2}H$ of groundwater in Wadi Baye

5.5.2 Radioactive isotopes Carbone-14

- Carbon-14 (Radiocarbon) is the radioactive isotope of carbon. Its long half-life of 5730 years makes it useful for late Quaternary chronology and now also extensively applied in hydrogeology to date groundwater. To maintain universality for dating purposes, ^{14}C activities must be normalized to a common $\delta^{13}C$ value. ^{14}C activities are referenced to an international standard known as modern carbon and expressed in pmc (percentage modern carbon). Schematic representation of relations between the 14C and 3H content in groundwater is show in Figure 5.19.

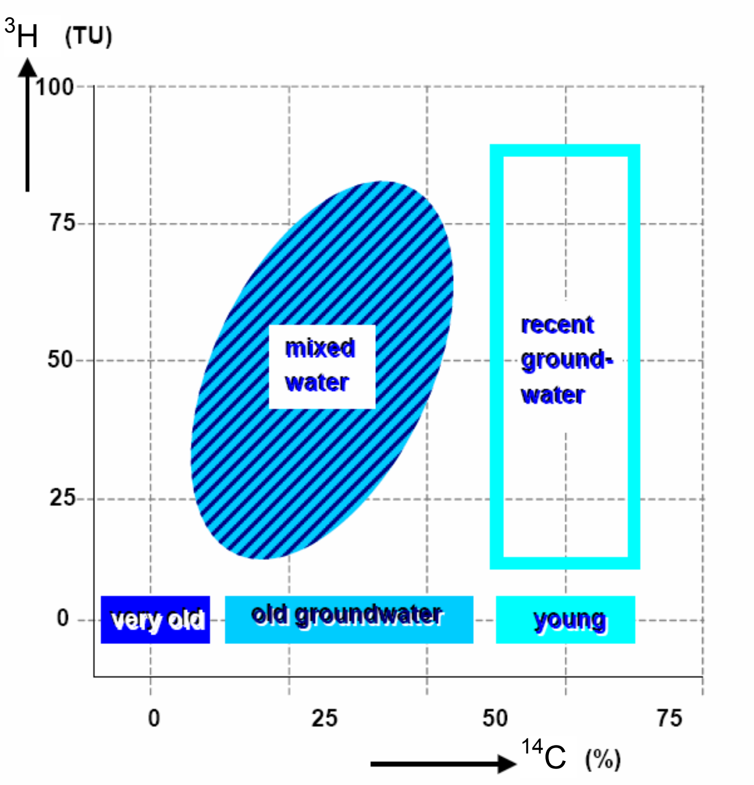

Figure 5.19 Relationship between ^{14}C and ^{3}H of groundwater

It can be concluded that:

- Recent groundwater is water that infiltrated not more than some tens of years ago.
- Young groundwater may have any age of hundreds of years.
- Old groundwater: thousands of years.

- Very old: fossil groundwater does not contain 3H and 14C and is several tens of thousands of years old.

Water which are relatively high in 3H and lower in 14C than recent water are likely to be mixtures of young and old water.

The radiocarbon contents of groundwater from deep and shallow aquifers range from 5 pmc down to 1.3 pmc. The presence of the older water component in these aquifers is suggested by the low radiocarbon contents recorded in the collected groundwater samples. Waters from the referred aquifers have signatures of a cooler climate indicated by the depleted $\delta^{18}O$ and $\delta^{2}H$ values. The detailed ^{18}O – ^{14}C relationship is shown in Figure 5.20 below.

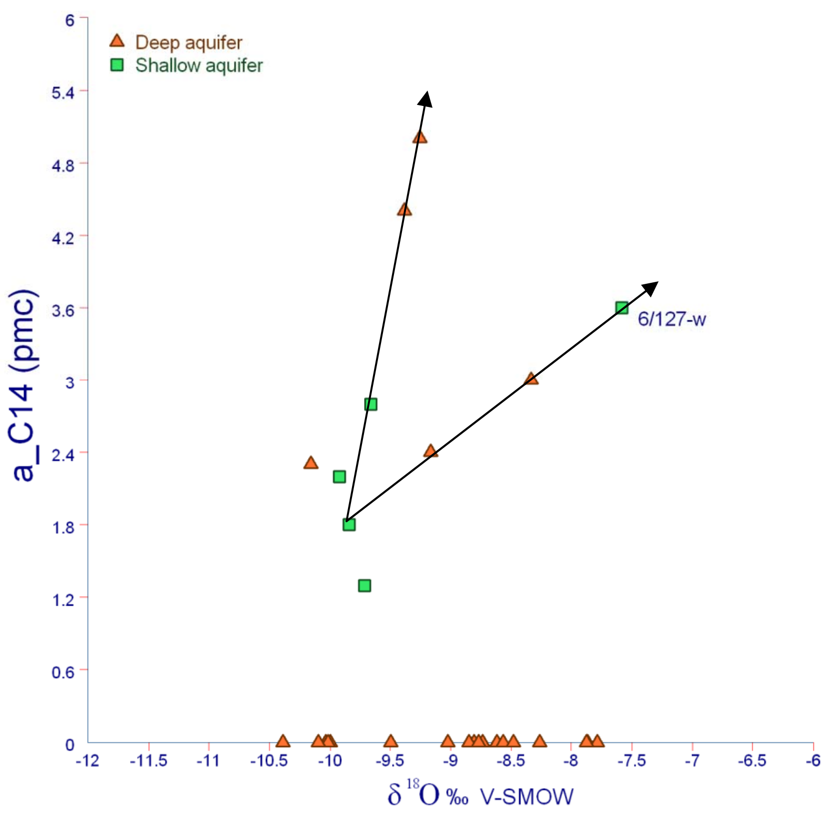

Figure 5.20 Relationship between $\delta^{18}O$ and ^{14}C of groundwater in Wadi Baye

5.6 Geochemical Processes

The evolution of hydrochemical characterizations in groundwater system is governed by varied factors, such as climate, topography and geomorphology, formation lithology, specific water-rock reactions, human activities, and especially in coastal region, seawater intrusion should be prominent as it is an issue of concern in hydro-geochemistry.

Libya lies in an arid and semi-arid region, featured with low precipitation less than 150 mm and high evaporation. Moreover, groundwater is buried deep in the fractured rocks with uncertain capability of water storage and transmissibility. Under such conditions, the renewal ability of groundwater is rather weak as recharge rate is so slow. Thus, groundwater all over Libya is characterized by high concentration of TDS, generally controlled by evaporation and minerals dissolution.

Besides, the concentrations of Cl^-, Na^+ and SO_4^{2-} in shallow groundwater presented a sharp decline at the point with an approximate distance of 70 km from the sea, and the break point is at about 50 km from the costal. The reasons to this phenomenon are discussed in the following part.

5.6.1 Mineral dissolution/precipitation

As described in Chapter 3, shallow aquifer mainly consist of limestone, marly limestone, dolomite and calcarenite (Eocene age), whilst the deep aquifer is composed mainly by marl sandstone with lots of carbonate minerals interbeded with calcite, dolomite etc. These soluble minerals at a certain extent change the composition of groundwater in this area. In order to examine the occurrence of these minerals dissolution, a geochemical modelling program PHREEQC was introduced to determine the degree of over- or under-saturation with such minerals as calcite, dolomite and gypsum in groundwater. For each mineral, the proximity to equilibrium was expressed as the saturation index (*SI*):

$$SI = \log \frac{IAP}{K}$$

where *IAP* is the ion activity product for a certain mineral and *K* is the equilibrium constant for the same mineral.

A *SI* of zero indicates that the solution is in equilibrium with a particular mineral. A $SI < 0$ indicates that the solution is under-saturated with respect to a particular mineral and a $SI > 0$ indicates over-saturation.

The calculated values of *SI* for the calcite, dolomite and gypsum of the groundwater samples are presented in Table 5.1 and Table 5.2. All the *SI* values for calcite and dolomite are greater than zero in both shallow and deep groundwater samples. The groundwater is therefore over-saturated with respect to these minerals, and precipitation results. The reactions are described as:

$$Ca^{2+} + CO_3^{2-} = CaCO_3$$

$$Ca^{2+} + Mg^{2+} + 2CO_3^{2-} = CaMg(CO_3)_2$$

The *SI* values of gypsum are all below zero, indicating gypsum is possibly dissolved by such groundwater as follows,

$$CaSO_4 \cdot 2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O.$$

Table 5.2 Saturation indices of selected minerals for groundwater in shallow wells

Well No.	Calcite	Dolomite	Gypsum	Well No.	Calcite	Dolomite	Gypsum
1	0.32	0.76	-0.15	**16**	0.30	0.65	-0.39
2	0.40	0.82	-0.11	**17**	0.34	0.49	-0.36
3	0.35	0.77	-0.14	**18**	0.32	0.77	-0.40
4	0.42	0.90	-0.12	**19**	0.47	0.87	-0.42
5	0.36	0.79	-0.13	**20**	0.41	0.83	-0.44
6	0.36	0.81	-0.12	**21**	0.50	0.91	-0.47
7	0.38	0.85	-0.13	**22**	0.40	0.75	-0.50
8	0.45	1.00	-0.13	**23**	0.39	0.75	-0.47
9	0.54	1.14	-0.15	**24**	0.38	0.62	-0.43
10	0.65	1.43	-0.17	**25**	0.48	0.90	-0.49
11	0.39	0.71	-0.14	**26**	0.48	0.93	-0.45
12	0.50	1.03	-0.21	**28**	0.50	0.94	-0.48
13	0.42	0.95	-0.23	**29**	0.30	0.54	-0.49
14	0.33	0.62	-0.21	**30**	0.88	1.73	-0.49
15	0.53	1.01	-0.25	**31**	0.69	1.26	-0.48

Table 5.3 Saturation indices of selected minerals for groundwater in deep wells

Well No.	Calcite	Dolomite	Gypsum	Well No.	Calcite	Dolomite	Gypsum
1	0.66	1.46	-1.14	**10**	0.48	1.20	-1.27
2	0.65	1.58	-1.22	**11**	0.42	1.11	-1.30
3	0.60	1.25	-0.84	**12**	0.65	1.55	-1.25
4	0.75	1.57	-0.82	**13**	0.63	1.52	-1.28
5	0.93	1.39	-0.84	**14**	0.56	1.38	-1.28
6	0.56	1.23	-1.03	**15**	0.67	1.59	-1.25
7	0.60	1.36	-1.21	**16**	0.62	1.45	-1.19
8	0.51	1.10	-1.16	**17**	0.53	1.30	-1.25
9	0.40	1.09	-1.31	**18**	0.43	1.03	-1.21

It is obvious that minerals dissolution or precipitation can only affect the concentration of Ca^{2+} and Mg^{2+} among all the cations. Besides, the process of minerals dissolution or precipitation is of a gradual change, and the lithology of aquifers is relative consistent in the study area. Thus, the saltation of ion concentrations along the flowpath is not the results of mineralization.

5.6.2 Evaporation and condensation

In the hydrological cycle the most frequent processes are the condensation and the evaporation in most arid or semi-arid regions. Evaporation of groundwater is strongly affected by its depth below ground - the shallower is it the higher the TDS of water due to evaporation.

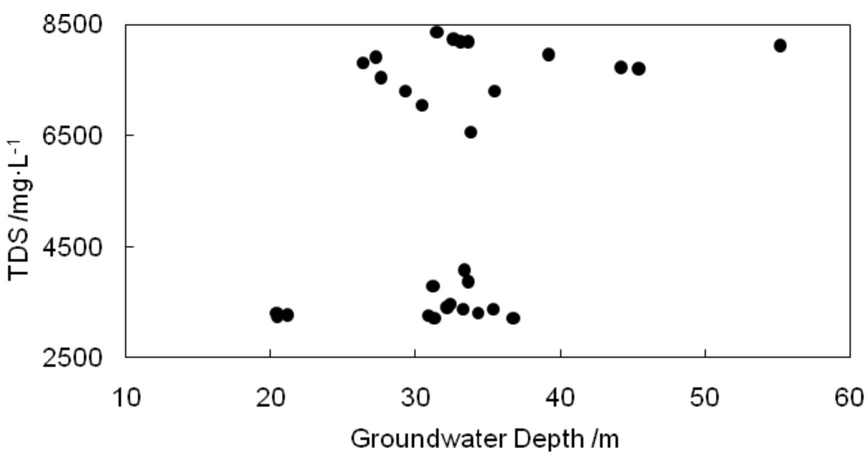

Figure 5.21 Relationship between TDS and the depth of groundwater table

The relationship between TDS and the depth of groundwater table (Figure indicates the depth varies in the range of 30~40 m while the TDS values are of 3000~4000 mg/l in several samples and 7000~9000 mg/l in others, indicating complete independence between these two indices. Therefore, it could be concluded that evaporation is not the principal factor contributed to the hydro-chemical evolution of shallow groundwater, not to mention deep groundwater with much deeper water level and huge thickness of impermeable cover layer. In summary, the saltation should not be derived by evaporation and condensation process.

5.6.3 Mixing

Considering the hydrogeology of this area, probable mixing processes here include mixture of groundwater with modern seawater and with ancient (palaeo-) saltwater. Further discussions on these are followed.

1) Modern Seawater intrusion

Saltwater intrusion is the movement of saline water into freshwater aquifers. Most often, it is caused by ground-water pumping from coastal wells. Mixing process happens in the seawater intrusion region which is determined by Ghyben-Herzberg model in this study due to no historical and observed records of seawater intrusion in Wadi Baye. This is assumed that the “natural” balance between sea water and fresh water system in the coastal areas. The “upconing” due to abstraction was not included in this section.

The first physical formulations of saltwater intrusion were made by W. Badon-Badon-Ghijben and A. Herzberg, thus called the Ghyben-Herzberg relation. It is known that sea water has a higher density (which is because it carries more solutes) than freshwater. If these two columns are connected at the bottom, then the pressure difference would cause a flow of saltwater column to the freshwater column until the pressure equalizes. The flow of saltwater inland is limited to coastal areas. Further inland, the freshwater column is higher due to the increasing altitude of the land and is able equalize the pressure from the salt water, stopping the saltwater intrusion. Therefore, in the coastal aquifers there exists a situation in which a steady interface between fresh and salt water is maintained through the movement of fresh water towards the sea (Figure 5.22).

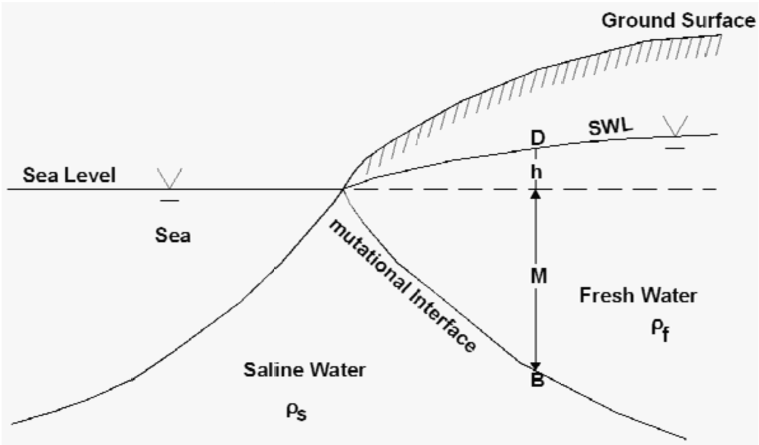

Figure 5.22 Conceptual model of the Ghyben-Herzberg relation

The relationship between the depth of the interface below sea level and the height of the free groundwater surface is described as Ghyben-Herzberg formula

$$\rho_s gM = \rho_f g(h_f + M)$$

where M is the depth of interface below sea level, h_f is the thickness of the freshwater zone above sea level, ρ_s and ρ_f are the density of saltwater and fresh water respectively.

The above equation can also be expressed as

$$M = \frac{\rho_f}{\rho_s - \rho_f} hf = \delta h_f \text{ where } \delta = \frac{\rho_f}{\rho_s - \rho_f}$$

Normally, Freshwater has a density of about 1.000 g/cm^3, whereas that of seawater is about 1.025 g/cm^3. The equation can be further simplified to

$$M = 40h_f$$

That is to say, for every foot of groundwater above sea level there are forty feet of fresh water below sea level. This relationship is such a simple solution that it is widely used to approximate the interface of intrusion behaviour although a number of assumptions do not hold in field cases.

Results of interface calculated by Ghyben-Herzberg formula are summarized in Table 5.4. In the calculation, two aquifers (Eocene-Miocene aquifer and Kiklah aquifer) were considered as one layer owning to frequent water exchange between them through fractures along the fault lines of Hun Garben.

Table 5.4 Interface elevation of seawater intrusion in Wadi Baye

Well No.	Groundwater Level (m)	Interface Elevation (m)	Well No.	Groundwater Level (m)	Interface Elevation (m)
1	28	-1120	**16**	55	-2200
2	28	-1120	**17**	58	-2320
3	31	-1240	**18**	62	-2480
4	33	-1320	**19**	59	-2360
5	27	-1080	**20**	74	-2960
6	30	-1200	**21**	69	-2760
7	32	-1280	**22**	73	-2920
8	36	-1440	**23**	76	-3040
9	32	-1280	**24**	74	-2960
10	36	-1440	**25**	74	-2960
11	35	-1400	**26**	72	-2880
12	48	-1920	**28**	72	-2880
13	56	-2240	**29**	74	-2960
14	50	-2000	**30**	75	-3000
15	49	-1960	**31**	71	-2840

Additionally, the interface elevation is associated with the depth of well and the groundwater level at each monitoring well. Figure 5.23 indicates the depth of pumping wells in shallow aquifer is much higher than the interface. It is inferred therefore that the remarkable changes of chemical components in shallow groundwater is not the results of seawater intrusion. As for the deep aquifer (Figure 5.24), the depths of Well 1 - Well 6 are below the interface, while others are above. That could to a certain extent explain the obvious higher concentration of TDS and ions in samples of Well 1~ Well 6 than that in others. Accordingly, mixing process induced by seawater intrusion is likely to make some contributions on the hydrochemical changes around wells of 1 - 6.

More indirect evidence can be obtained from the isotopic data. As shown in Figure 5.17, the two clusters for deep wells divided by $\delta^{18}O$, which is supposed to the results of different recharge in most cases. Coincidently, this classification is just in accordance with that by the relationship between well depth and seawater intrusion interface elevation in Figure 5.24. Thus, it is further confirmed that the mixing process between groundwater and modern seawater has an effect on the hydrochemical evolution of deep groundwater.

However, although separation was also found in $\delta^{18}O$ among shallow groundwater samples as Figure 5.17 shows, the same conclusion was not drawn for the depths of all the shallow wells are above the interface (Figure 5.23). So there other mixing process may occur, most probably with ancient saltwater.

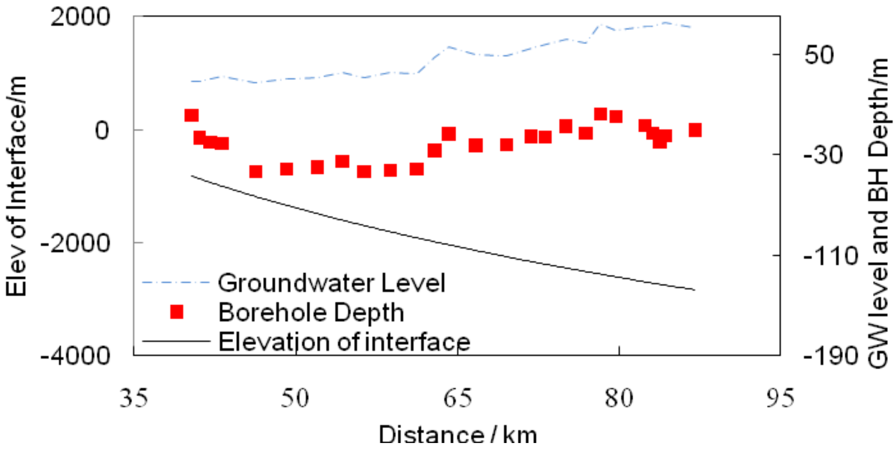

Figure 5.23 Comparison of salt-fresh water interface, groundwater level and depth of wells for shallow aquifer

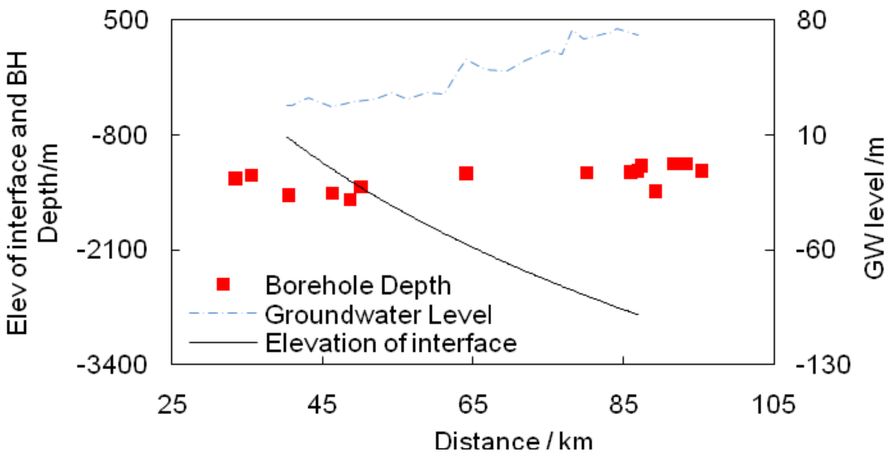

Figure 5.24 Comparison of salt-fresh water interface, groundwater level and depth of wells for deep aquifer

2) Mixing with palaeo-saltwater

As described in the review of the geological history(Mohamed Said 1981), this area experienced several transgressions since Cretaceous Period. During the long period, the Upper Cretaceous-Paleocene transgression is one of the most important stages. After the deposition of the Paleocene sediments, a regressive phase accompanied by accumulation of shallow water marine and brakish deposits with occasion of oscillation of the depth of depositional basin, which continued up to the lower part of the Upper Eocene, when the continental environment took place. A new transgression occurred during the Middle Miocene, when marine formation was deposited; however, by the end of Middle Miocene, the sea receded, and the shallow water marine sediments were gradually replaced by brackish and fresh-water deposits, and a continental environment prevailed again, lasting throughout the Pliocene and Quaternary. The ancient saltwater in the deposits were gradually mixed with and replaced by freshwater during Quaternary period, and in some plains saltwater entrapped in deposits forms some saltwater lens with marine features (Figure 5.25).

In this study, sampling wells of No. 1 - No. 14 for shallow groundwater are distributed along a strip near the boundary between the Eocene and the Miocene while others are located in the Eocene strata (Figure 5.26). As transgression happened in the Miocene Period, the probable interface between saltwater and freshwater should be in the Eocene strata. According to the results of hydrogeochemical analysis, saltation of concentrations were found between Well 16 and Well 17 with great increase of TDS from 3792 mg/L in Well 17 to 4075 mg/L in Well 16. From this, it can be inferred that the saltation of chemical composition in shallow groundwater is induced by mixing with ancient saltwater. On the other hand, the interface of ancient saltwater was determined at about 70 km off the coast, just between Well 16 and 17 (Figure 5.26).

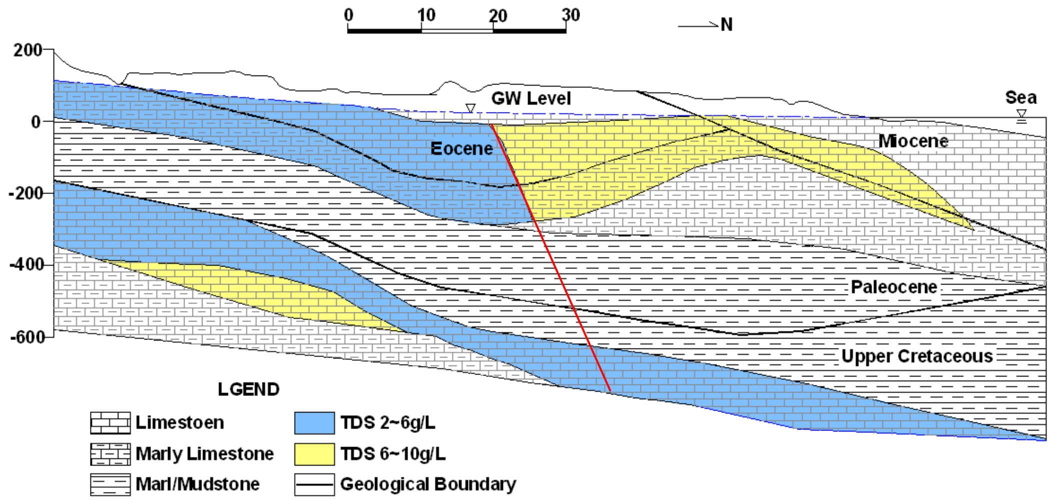

Figure 5.25 Hydrogeological profile of I-I in Wadi Bay (1970s) cross-section I-I'missing

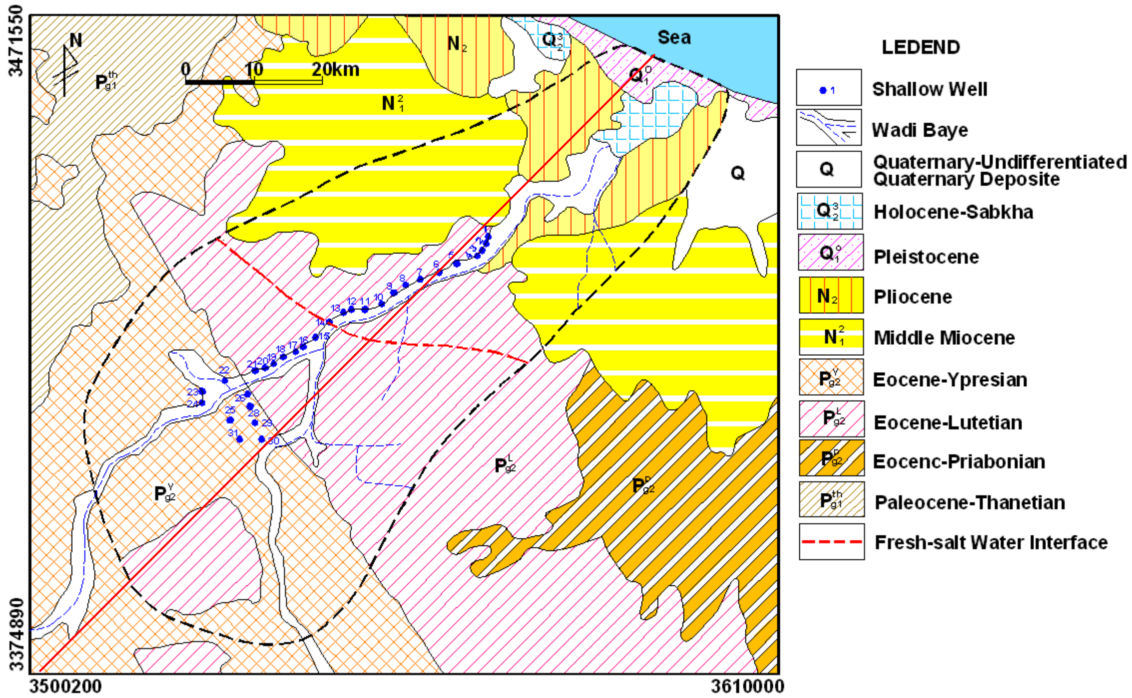

Figure 5.26 Interface between freshwater and ancient saltwater cross section

5.6.4 Ion-exchange

Geological investigation indicates seawater intrusion may have occurred since the Cretaceous period in this area. During seawater intrusion, more Na^+ carried by seawater broke the equilibrium of its distribution between the water and the solid, then

Ca^{2+} was displaced by Na^{+} from seawater to give an ion-exchange reaction. After that, fresh water re-entered the marine stratum, and the reverse process occurred.

Furthermore, rNa^{+}/rCa^{2+} values of groundwater provide hydrochemical evidence for the above reactions. From Figure 5.27, it can be inferred that loss of Ca^{2+} exists in most parts of the study area with rNa^{+}/rCa^{2+} values over 1. That is usually caused by the calcium precipitation and ion-exchange reactions such as

$$Ca^{2+}(water)+HCO_3^{-}+Na^{+}(solid)\rightarrow Na^{+}(water)+HCO_3^{-}+Ca^{2+}(solid)$$

$$Ca^{2+}(water)+Na^{+}(water)+HCO_3^{-}+Na^{+}(solid)\rightarrow 2Na^{+}(water)+HCO_3^{-}+Ca^{2+}(solid)$$

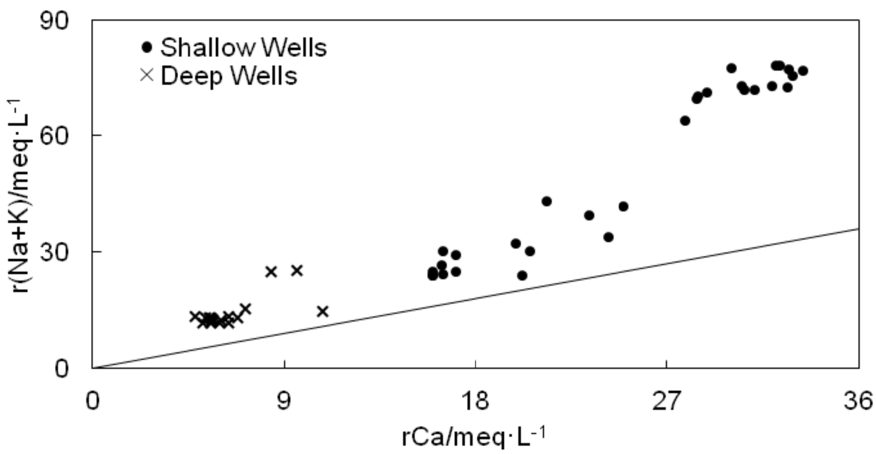

Figure 5.27 Scatter plot of rNa^{+}/rCa^{2+} for water samples in Wadi Baye

In conclusion, the remarkable chemical changes for shallow groundwater at around 70 Km off the coast are probably related with ancient saltwater, while for deep groundwater the chemical saltation at 50 Km off the coast is more likely to be the results of modern seawater intrusion.

5.7 Summary

A series of hydrochemical techniques and indices were employed to study the spatial and temporal variations of the groundwater hydrochemistry in the shallow and deep aquifer systems, such as piper diagram, descriptive statistics, the ratio coefficient of the main ions and isotopic method. In general, TDS and the concentration of main ions in groundwater are high, especially in shallow groundwater. Ion concentrations of groundwater in upstream are much lower than that in the downstream, and a dramatic fall occurs at the Middle part of study area. The shallow groundwater types divided according to the Piper classification are $Cl{\cdot}SO_4$-$Na{\cdot}Ca$ and $Cl{\cdot}SO_4$-Na; the deep groundwater types are more complex, but the main types are also $Cl{\cdot}SO_4$-Na and $Cl{\cdot}SO_4$-$Na{\cdot}Ca$. The isotope signature indicates that the sources of groundwater between upstream and downstream are difference. It is found that the shallow groundwater is mainly influenced by the palaeo-saline hydro-environment off coast 70 Km, the deep groundwater geochemistry is impacted by mixture with the modern sea-sea-water around 50 Km off the coastal line.

Chapter 6 3D NUMERICAL MODELLING OF GROUNDWATER FLOW

6.1 Introduction

A hydrogeological conceptual model is a conceptual presentation of the combination of geological and hydrogeological conditions and is necessary to give answers about changes in hydrogeological environment. Whilst the further numerical model will be based on the conceptual model, it is a mathematical realization of the input parameters described within the above hydrogeological conceptual model. It is considered that by this model actual structure of the groundwater flow system could reappear as well as the groundwater movement.

Although limitations exist in some aspects such as lack of groundwater observation data in this study area which may hold us back to obtain the high-precision simulation in the research, groundwater numerical simulation can still reveal the macro dynamic features of groundwater and identify hydrogeological conditions through inverse simulations. For this reason, 3D numerical modeling of groundwater is a useful tool to improve our understanding of groundwater circulation characteristics for rational development and utilization of groundwater resources, and to provide more evidence for groundwater management strategy.

6.2 Hydrogeological conceptual model

Prior to simulating the ground-water system, a conceptualization of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural system because inclusion of all of the complexities of the natural system into a computer model is not feasible given the existing knowledge of the subsurface and current computer capabilities.

6.2.1 Aquifers and Confining Unit

The groundwater flow system can be characterized as a multi-aquifer system comprising two permeable layers separated from each other by a regional confining unit, based on existing and new geologic and hydrologic data.

1) A shallow unconfined aquifer

Unconfined aquifer distributed widely in the whole study area. Miocene fractured aquifer which consisted of limestone and calcarenite with good permeability dominated in the coastal plain, while inland plains widespread Eocene fractured aquifer composed by limestone with moderate permeability.

Most municipal water-supply systems use the sand and gravel aquifer or the lower bedrock aquifer. Most ridge-top communities are on private water supply and use the Wonewoc sandstone or a combination of the Wonewoc sandstone and the Tunnel City Group as shallow outcrops.

2) An aquitard

An impermeable layer underlines Eocene-Miocene formations. It is made up of marl, calcareous marl and limestones of Paleocene and Late cretaceous.

3) A deep confined aquifer

The early Cretaceous Kiklah aquifer widely distributed and buried deeply. Its thickness ranges from 30m to 182 m. This aquifer is the layer of interest in this study for it is the main aquifer of current groundwater exploitation,.

Both of the unconfined and confined aquifers were generalized as heterogeneous isotropic aquifers due to variation of lithology and thickness in the whole region. In general, these three layers constituted a 3D hydrogeological system with the uniform hydraulic connection (see the conceptual model in Figure 3.18).

6.2.2 Boundary Conditions

The northern boundary of the unconfined aquifer is regarded as a constant head boundary with the water level of 0 m along the Mediterranean coastline. As there is no water level observation data along the boundary of unconfined aquifer, the other part is considered as a flow boundary. For the deep confined aquifer, the same boundary conditions as unconfined aquifer were set in the model, as shown in Figure 6.1.

According to the analysis of groundwater circulation features, the top boundary of shallow aquifer is taken as the opening boundary which accepts the infiltration recharges and pumping discharge. The bottom of confined aquifer is bounded by mudstone and marlstone which is classified as an impermeable boundary.

6.2.3 Groundwater Flow Characteristics

Contour map of Groundwater level demonstrated that natural hydraulic gradient is small in range of 4.5×10^{-4}~2.4×10^{-3} for the shallow aquifer gradient and 1.2×10^{-3}~5.7×10^{-3} for the deep aquifer. It is supposed that the groundwater movement is in accordance with Darcy’s law due to gentle flow field and slow velocity of groundwater. Water exchange exists between shallow and deep aquifer through leakage flow. Consequently, the characteristics of whole groundwater flow system can be described as a three dimensions transient flow.

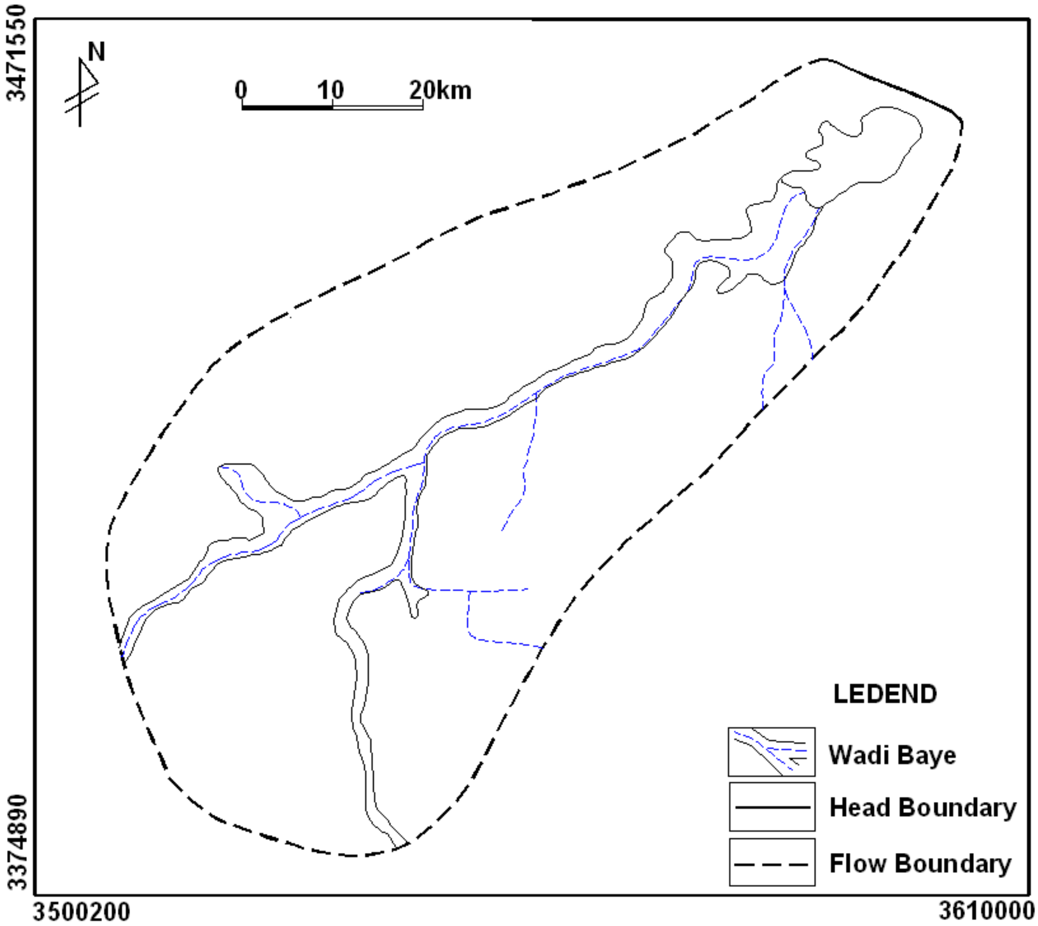

Figure 6.1 Distribution of boundary types

6.3 Hydrogeologic Parameters

Hydraulic conductivity, specific yield and storage coefficient are the main hydrogeologic parameters in groundwater numerical simulation. Initial estimates of these parameters were based on existing and on new geologic and hydrologic data.

6.3.1 Hydraulic conductivity

1) Hydraulic conductivity of confined aquifer

The saturated horizontal hydraulic conductivities of the geologic units were estimated by Dupuit formula using data from the single-hole steady flow pumping tests. The pumping test data in this study was obtained from the previous investigation carried out by Halcrow (Halcrow, 2001). That contains the data of 17 deep groundwater wells in the study area and its surroundings Figure 6.2. The detailed data of pumping tests at each well are summarized in Table 6.1

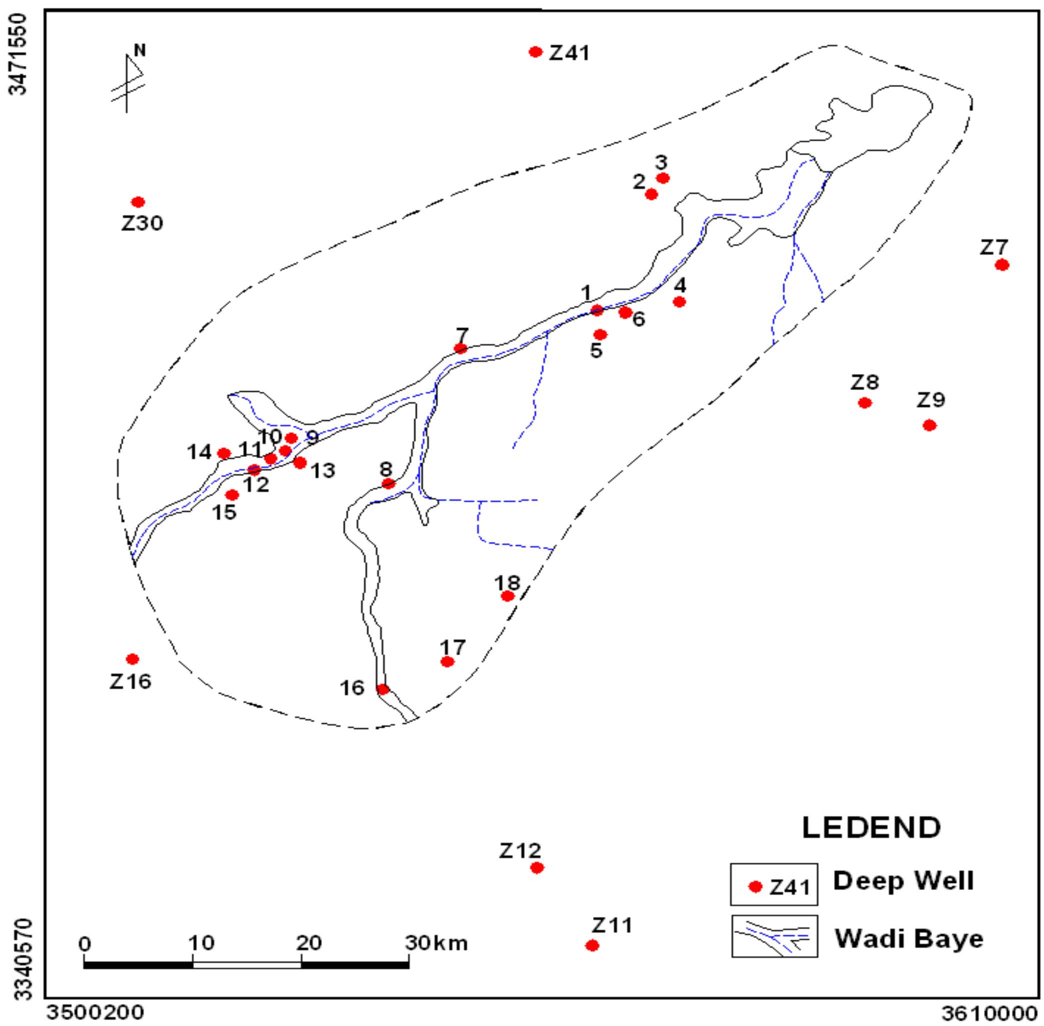

Figure 6.2 Locations of pumping test wells

Table 6.1 Data of pumping tests

Well	Well diameter (mm)	Aquifer thickness (m)	Flow (m^3/d), Drawdown(m)
1	473	243	(942, 5.5);(2039, 13.5);(2023, 19.5); (3205, 28.6);(4276, 44.5)
4	473	117	(250, 0.5);(855, 2.15);(2238, 8.75); (3706, 18.4);(5184, 30.6)
5	473	123	(1624, 4.8);(2246, 8.5);(2635, 11.5); (3110, 15.5);(3585, 19.9)
6	473	190	(3024, 8);(6073, 24);(9141, 44); (11500, 58.2);(12839, 75.3)
7	473	113	(518, 9);(717, 14.3);(967, 19.5); (1183, 24.5);(1486, 30)
9	473	83	(4303, 51.5)
13	473	77	(4682, 67.6)
17	473	135	(10230, 83)
18	473	119	(17167, 83)
Z7	473	165	(5659, 35.1)
Z8	473	77	(2108, 28.2)
Z9	473	66	(1011, 20)
Z11	473	146	(1296, 7.2);(2506, 17.4);(3542, 26.6); (4104, 35.5);(5012, 42.7)
Z12	473	213	(475.2, 1.5);(1192, 4.6);(2013, 10);(2661, 15.3)
Z16	473	78	(3646, 45.1)
Z30	473	101	(2998, 46)
Z41	473	101	(4838, 31)

Based on the data of main pumping well, the hydraulic conductivity (K) was calculated by Dupuit formula

$$K = \frac{Q \ln\left(\frac{R}{r}\right)}{2\pi Ms}$$

And the influence radius (*R*) was determined using the formula

$$R = 10s\sqrt{K}$$

where Q is water inflow in a single well (m^3/d); M is thickness of confined aquifer (m); *K* is hydraulic conductivity (m/d); *R* and *r* are influence radius and pumping well radius respectively (m); *s* is drawdown of groundwater level (m). The calculated results of *K* and *R* are shown in Table 6.2.

Table 6.2 Results of *K* and *R*

Well	*R* (m)	*K* (m/d)	Well	*R* (m)	*K* (m/d)
1	150	0.47	**4**	155	1.84
5	155	1.76	**6**	455	1.30
7	122	0.39	**9**	547	1.13
13	690	1.04	**17**	585	2.16
18	1224	2.17	**Z7**	356	1.03
Z8	280	1.00	**Z9**	170	0.72
Z11	242	0.90	**Z12**	69	0.80
Z16	482	1.14	**Z30**	381	0.69
Z41	399	1.66			

Then, the deep confined aquifer was divided into five subareas with different values of hydraulic conductivity (Figure 6.3 and Table 6.3) according to the results of hydraulic conductivity and previous results of Halcrow (2001), as well as various geological factors (e.g. the formation ages, structures and lithology).

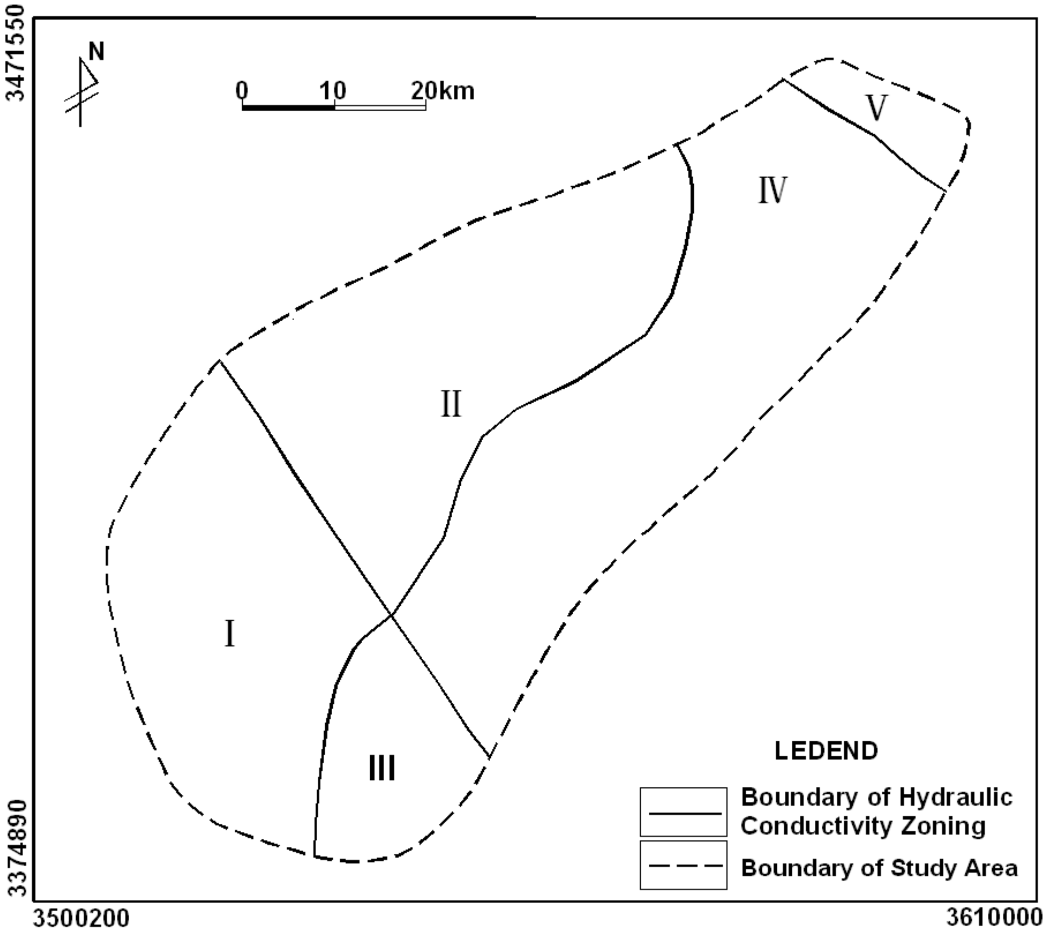

Figure 6.3 Partitions of hydraulic conductivity for deep aquifer

Table 6.3 Initial values of hydraulic conductivity for deep aquifer

Zone ID	I	II	III	IV	V
K（**m/d**）	1	0.4	2	3	0.4

2) Hydraulic conductivity of unconfined aquifer

No measurements of the hydraulic conductivity of this aquifer have been made in this area, so parameter values were determined according to the reference values in “The Handbook of Groundwater Engineering” and other text books, taking several factors into account such as the formation age, lithological characteristics and etc. These values were then subject to calibration in the modelling processes. The hydraulic conductivity of fine sand and silt is in the range of 1~10 m/d, while the value of limestone and karst limestone ranges from 10^{-1} m/d and 10^{4} m/d.

Since fractures in this aquifer are not so well developed, lower values were selected for the model. Partitions of shallow aquifer permeability coefficient and initial values were showed in Figure 6.4 and Table 6.4.

Table 6.4 Initial values of hydraulic conductivity for shallow aquifer

Zone ID	I	II	III	IV
Lithology	Fine sand, Limestone	Limestone	Limestone, Calcareous marl	Limestone
Empirical value (m/d)	10^{-1}~10^{4}	10^{-1}~10^{4}	10^{-1}~10^{4}	10^{-1}~10^{4}
Initial value (m/d)	3.0	5.0	1.0	5.0

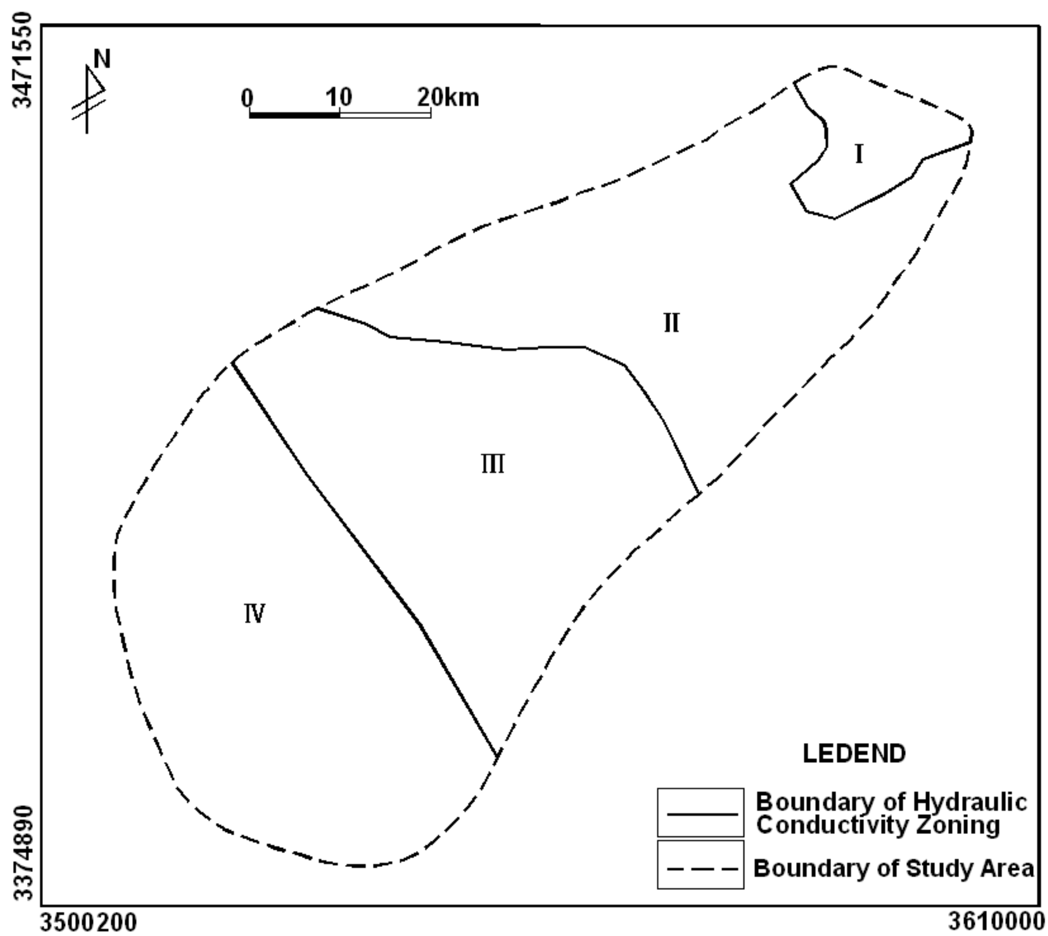

Figure 6.4 Partitions of hydraulic conductivity for shallow aquifer

3) Hydraulic conductivity for the aquitard

The aquitard in the study area is made up of marl, mudstone and marly limestone which were formed in Paleocene and late Cretaceous. The lithology and hydrology properties of rocks were constant in the whole region, so the entire aquitard permeability coefficient was assigned as one partition with an empirical value of 1.0×10^{-5}m/d for most clay and shale at 10^{-4}~10^{-8} m/d.

6.3.2 Specific yield and storage coefficient

Specific yields (μ) were determined according to the empirical values provided in "Manual of water supply hydrogeology" and "The Handbook of Groundwater Engineering" as there is no observed data for its calculation in this area. The storage coefficients (μ*) were collected from Halcrow's findings (Halcrow, 2001). The parameters of each aquifer were showed in Table 6.5.

Table 6.5 Initial values of specific yield and storage coefficient

Layer	Empirical value		Initial value	
	μ	μ*	μ	μ*
Shallow aquifer	0.008~0.1	—	0.008	—
Aquitard	—	—	—	1.0×10^{-5}
Deep aquifer	—	—	—	2.1×10^{-3}

Note：As pores and fractures generate poorly in the area, the lower values were selected in calculations.

6.4 Sources and Sinks

The groundwater recharge mainly includes infiltration of rainfall and lateral runoff of groundwater for shallow aquifer. Because of deeply buried water table, evaporation of shallow groundwater can be ignored. The deep confined aquifer is recharged mainly by groundwater lateral runoff with discharge way of lateral outflow and artificial pumping.

6.4.1 Precipitation infiltration

The precipitation infiltration which is one of the important sources of the recharge can be pressed as:

$$Q = F \times \alpha \times X \times 1000$$

where Q is precipitation infiltration amout (m^3/a); α is infiltration coefficient; F is study area (km^2); X is annual precipitation (mm); 1000 is the unit conversion factor.

The rate of precipitation infiltration is usually affected by many factors such as total rainfall, intensity and duration of precipitation, lithology of surface layer, thickness of vadose zone, landuse type and etc. Empirical values were adopted in the model according to the lithology description which is the only available information in this area. Partitions of infiltration coefficient zoning and precipitations were present in Figure 6.5 and Table 6.6. The net recharge from precipitation and evaporation to be included in the models is also subject to calibration. It could be quite minor given the climate in the region but it's greater in coastal area than inland of the Wadi. The contours were interpolated according the weather stations around the study area for an approximate starting point of the modelling exercises.

Table 6.6 Results for precipitation infiltration coefficient

Zone ID	Lithology	Empirical values of α	α adopted
I	Fine sand	0.08~0.18	0.13
II	Karst mineralize limestone weakly	0.01~0.15	0.05
III			0.02
IV			0.05

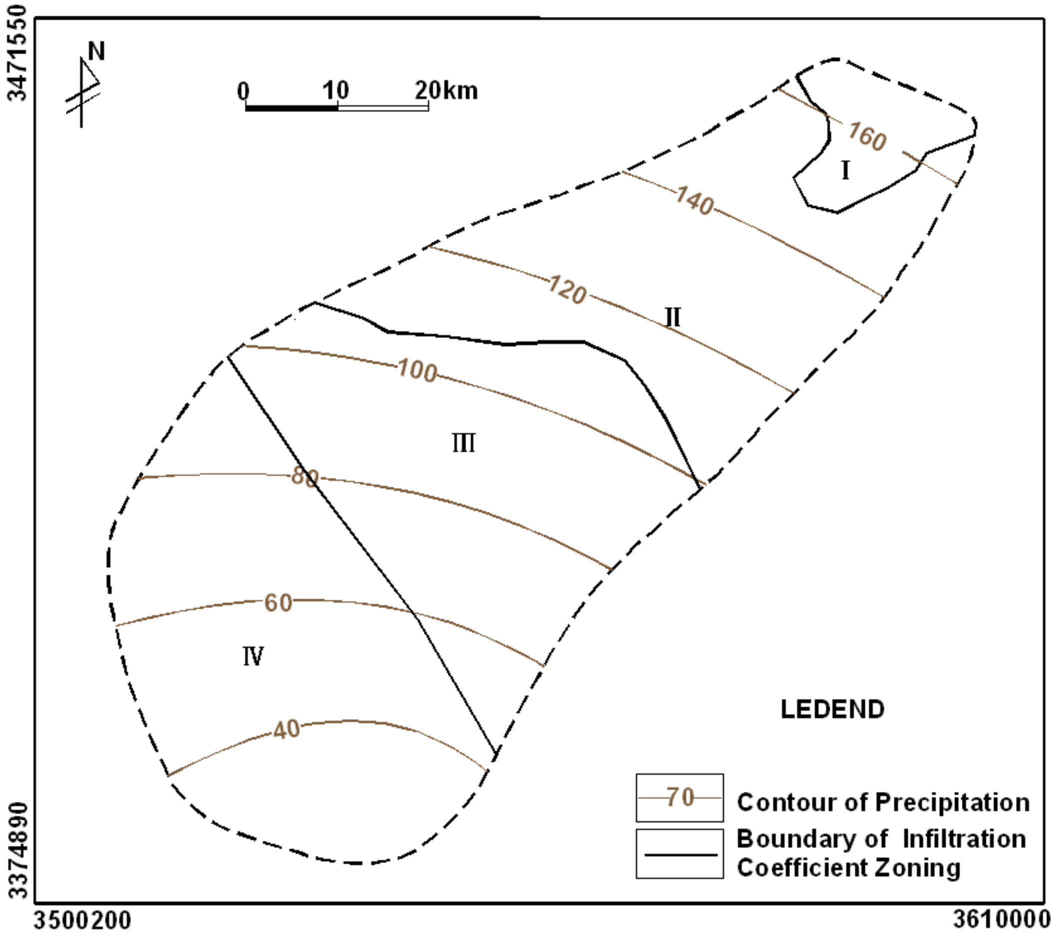

Figure 6.5 Partitions of precipitation and infiltration coefficient

6.4.2 Groundwater lateral runoff

The initial flux at lateral boundary is calculated by Darcy's law according to the water head and the permeability coefficient,

$$Q=K\cdot I\cdot B\cdot M\cdot \Delta T\cdot \sin\theta$$

where Q is amount of groundwater lateral runoff (m^3/d); K is hydraulic conductivity (m/d); I is groundwater hydraulic gradient; B is width of cross section (m); M is aquifer thickness (m); ΔT is calculated time (d); θ is the angle between groundwater flow and cross section.

The calculation cross-sections were divided as Figure 6.6 and Figure 6.7 for shallow aquifer and deep aquifer respectively, according to the local geology (lithology and structure), hydraulic conductivity and land use along the boundary. The results are summarized in Table 6.7and Table 6.8.

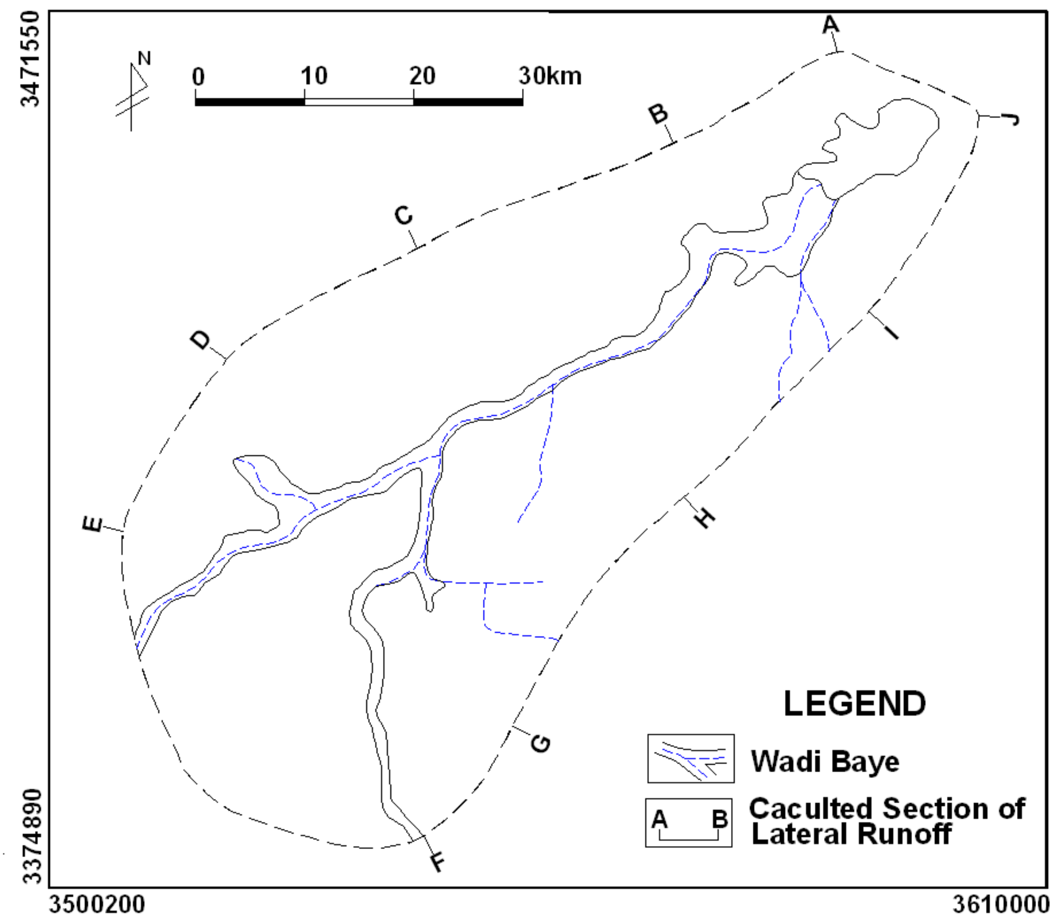

Figure 6.6 Calculation sections of lateral runoff in shallow aquifer

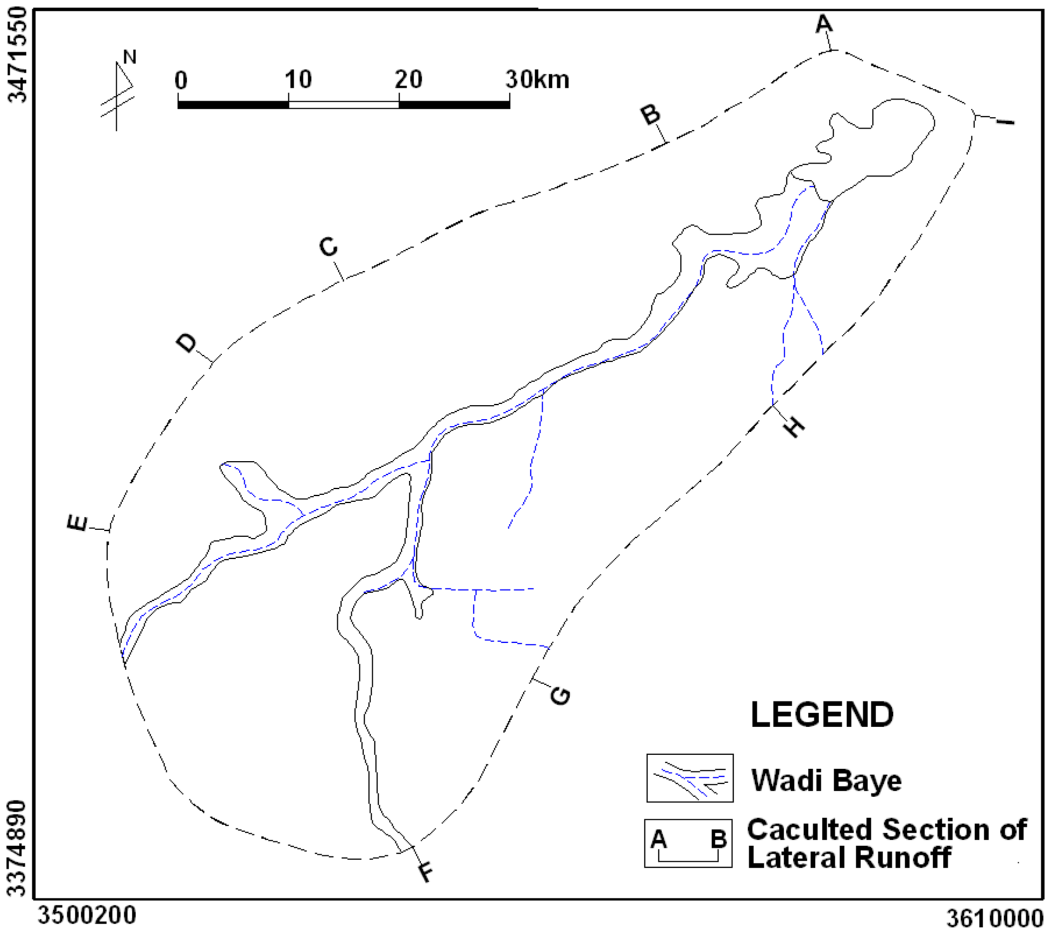

Figure 6.7 Calculation sections for groundwater lateral runoff in deep aquifer

Table 6.7 Calculated results of shallow groundwater lateral runoff

Lateral runoff	Section ID	Area (10^4m^2)	sinθ	I	K (m/d)	Q (10^4 m^3/d)	Total (10^4 m^3/d)
Discharge	A-B	523.28	0.37	0.0012	3	0.70	2.04
	B-C	508.1	0.37	0.0011	3	1.03	
	C-D	363.92	0.09	0.0019	5	0.31	
Recharge	D-E	328.76	0.56	0.0007	5	0.64	5.82
	E-F	544.88	0.7	0.00056	5	1.07	
	F-G	299.92	0.51	0.00045	5	0.34	
	G-H	603.65	0.18	0.0021	5	1.14	
	H-I	679.68	0.38	0.0013	5	1.68	
	i-J	643.90	0.38	0.0013	3	0.95	

Table 6.8 Calculated results of deep groundwater lateral runoff

Lateral runoff	Section ID	Area ($10^4 m^2$)	sinθ	I	K (m/d)	Q (10^4 m^3/d)	Total (10^4 m^3/d)
Discharge	A-B	262.30	0.37	0.0024	3	0.70	1.64
	B-C	529.94	0.95	0.0025	0.4	0.50	
	C-D	168.48	0.51	0.0018	0.4	0.06	
	F-G	221.36	0.71	0.0012	2	0.38	
Recharge	E-F	568.89	0.76	0.0014	1	0.61	6.23
	D-E	147.82	0.07	0.0024	1	0.02	
	G-H	144.50	0.83	0.0017	3	0.61	
	H-I	569.14	0.73	0.004	3	4.99	

6.4.3 Groundwater Withdrawals

1) Deep groundwater

Two investigations of groundwater exploitation were carried out in 1973 1973) and 2001 (Halcrow, 2001). Records of 4 pumping wells in Wadi Bay irrigation area were shown in Table 6.9. Yield of these four pumping wells decreased by an average of 15% from 1973 to 2001with reduction rate of 0.54% per year. Therefore, with this rate of reduction and conditions in 1973, exploitation quantity of 2010 was estimated as a total exploitation amount of 53315 m^3/d for deep groundwater. The results are shown in Table 6.10.

2) Shallow groundwater

According to the records of hydrogeologic investigation report in 1976, the total yield of WS1 and E2 in south of Wadi Bay were 1.84×10^6 m^3/a with an average of 2523 m^3/d for each. Base on the records in 1976, exploitation quantity for shallow groundwater was calculated using the reduction rate of 0.54%. to be 2060 m^3/d for a single well and 61800 m^3/d for 30 wells in 2010.

Table 6.9 Well exploitation quantity of Wadi Bay in 1973 and 2001

Well	Yield (L/s)		Reduction rate (%)
	In 1973	In 2001	
1	60	50	17
4	83	75	10
5	57	45	21
6	100	85	15
Total	300	255	15

Table 6.10 Exploitation quantity of deep wells in 2010

Well	Yield (m^3/d)	Well	Yield (m^3/d)	Well	Yield (m^3/d)
1	4320	2	200	3	200
4	3480	5	3890	6	7340
7	820	8	820	9	2600
10	2300	11	2300	12	2300
13	2575	14	2300	15	2300
16	4970	17	5400	18	5200

6.5 Three-Dimensional Numerical Simulation

6.5.1 Mathematic model

Based on the hydrogeological conditions, groundwater flow can be conceptualized as 3D heterogeneity isotropic transient flow, which was expressed as following differential equation and definite conditions (Yang et al. 1999).

$$\begin{cases} \frac{\partial}{\partial x}\left[K\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K\frac{\partial h}{\partial z}\right]+W=S\frac{\partial h}{\partial t}, & (x,y,z)\in\Omega,\ t>0 \\ K\left(\frac{\partial h}{\partial x}\right)^2+K\left(\frac{\partial h}{\partial y}\right)^2+K\left(\frac{\partial h}{\partial z}\right)^2-\frac{\partial h}{\partial z}(K+P)+P=\mu\frac{\partial h}{\partial t}, & (x,y,z)\in\Omega,\ t>0 \\ H(x,y,z,t)_{t=0}=h_0(x,y,z,t) & (x,y,z)\in\Omega, t=0 \\ H(x,y,z,t)_{\Gamma_1}=h_1(x,y,z,t) & (x,y,z)\in\Gamma_1,\ t>0 \\ K_n\left.\frac{\partial h}{\partial n}\right|_{\Gamma_2}=f_1(x,y,z,t) & (x,y,z)\in\Gamma_2,\ t>0 \end{cases}$$

where Ω is the scope of simulated area; K is hydraulic conductivity (m/d); S is specific storage (1/m); μ is specific yield; W is the volume of sources and sinks; P are infiltration rate; h (x, y, z, t) is hydraulic head; h_0 is initial head (m); h_1 is hydraulic head of first boundary (m); f_1 is flux of second boundary ($m^3/m^2 \cdot d$); K_n is hydraulic conductivity at the boundary (m/d); $\boldsymbol{n}$ is the outflow direction against the boundary; Γ_0 is top boundary of simulated area, that being the groundwater table; Γ_1 is the first boundary of simulated area; Γ_2 is the second boundary of simulated area. Combining with the initial conditions and the boundary conditions, the numerical model was constructed.

6.5.2 Solution of numerical model

Analytical solutions of the above equations are rarely possible except for very simple systems, therefore numerical methods must be employed to obtain approximate solutions.

Visual MODFLOW program was applied to simulate the three-dimensional flow system in the Wadi Baye model. It is developed by Waterloo Hydrogeologic Inc based on USGS MODFLOW (). The program also combines MODPATH, MT3D/RT3D, and WinPEST with a graphical interface available. It has been widely used in industry and academia worldwide so far for groundwater studies and data visualization.

6.5.3 Model Grids

The three-dimensional model covers an area of approximately 3650 km^2 that is subdivided into 2987 nodes. The row and column dimension of each node is uniform throughout the model area, with each node measuring 1200 m on a side and having an area of about 1.44 km^2 (Figure 6.8).

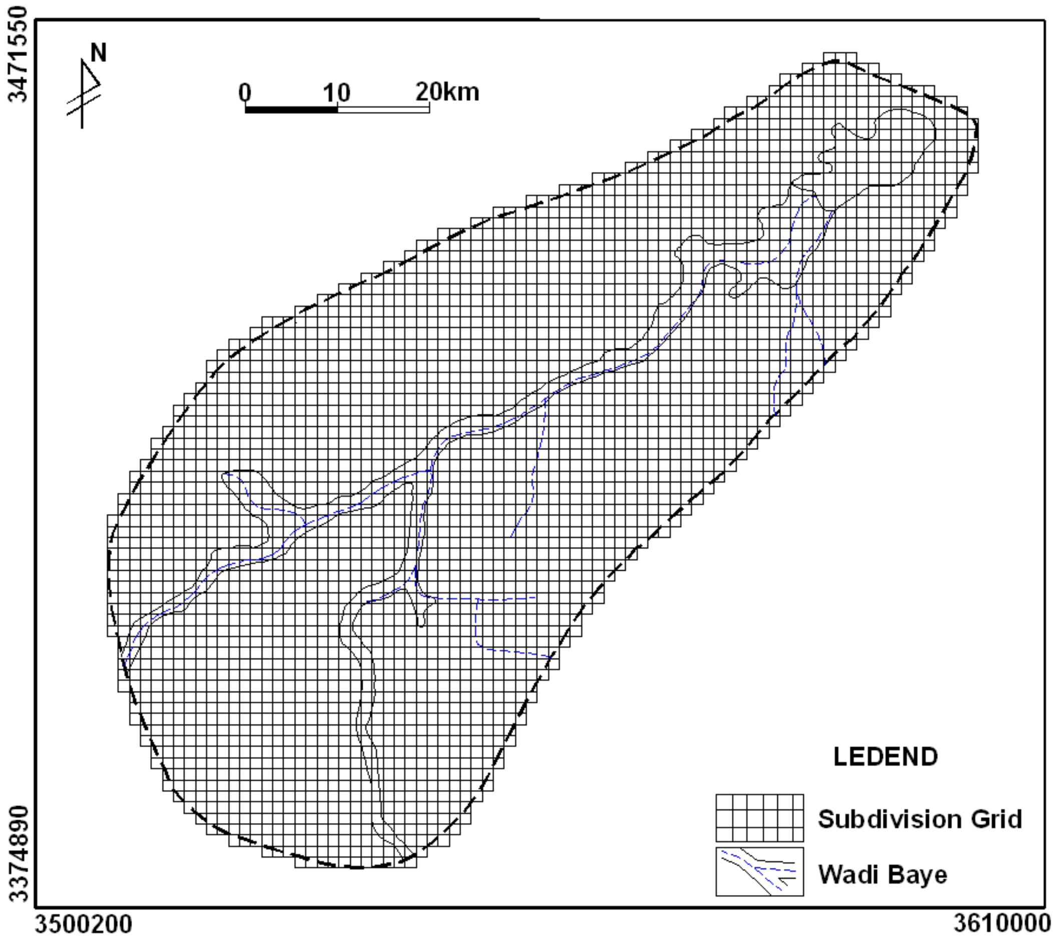

Figure 6.8 Finite-difference grids for the study area model

6.5.4 Initial heads and simulated periods

Groundwater levels of February 2009 were taken as the initial heads for shallow and deep groundwater (Figure 6.9, Figure 6.10). The simulation time covered a period of 620 days from February 2009 to November 2010. There are some other data in the past, e.g. from Gefli (1973) and Halcrow (2001) but they are not consistent for such a modelling study.

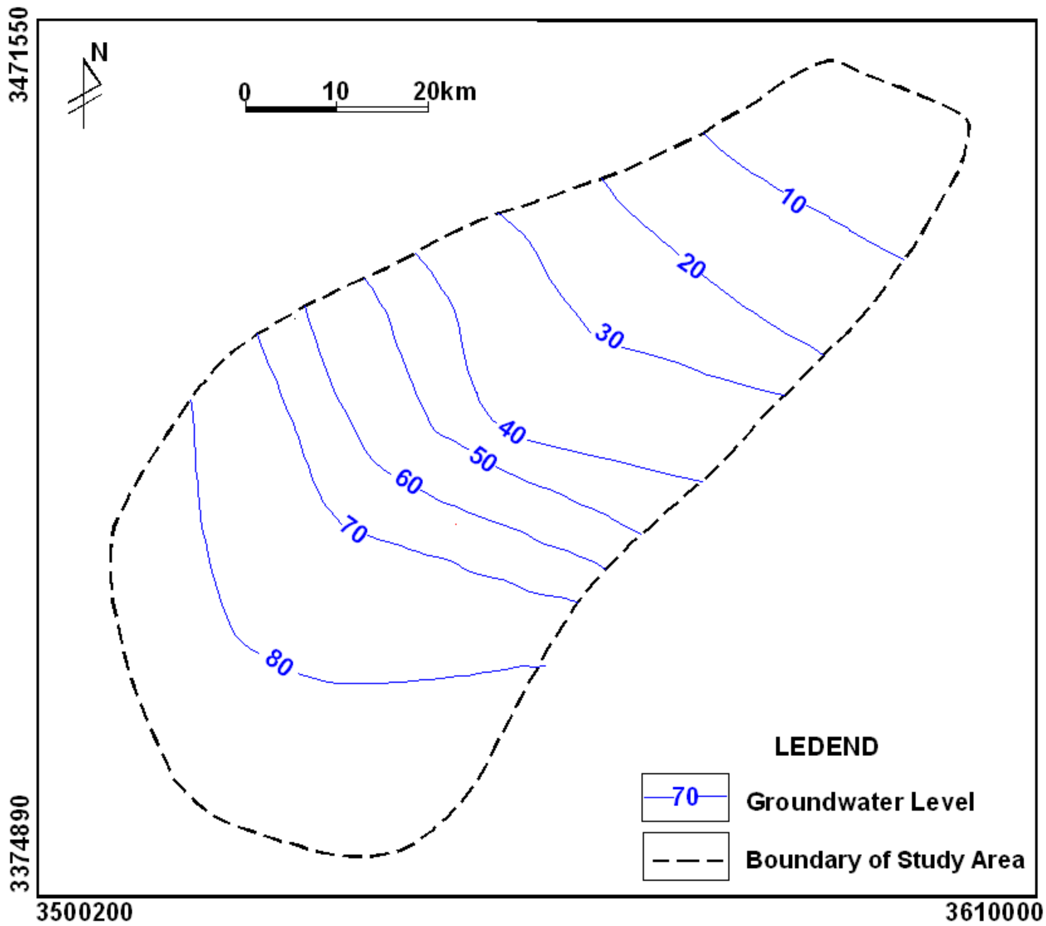

Figure 6.9 Initial heads contour map of shallow groundwater

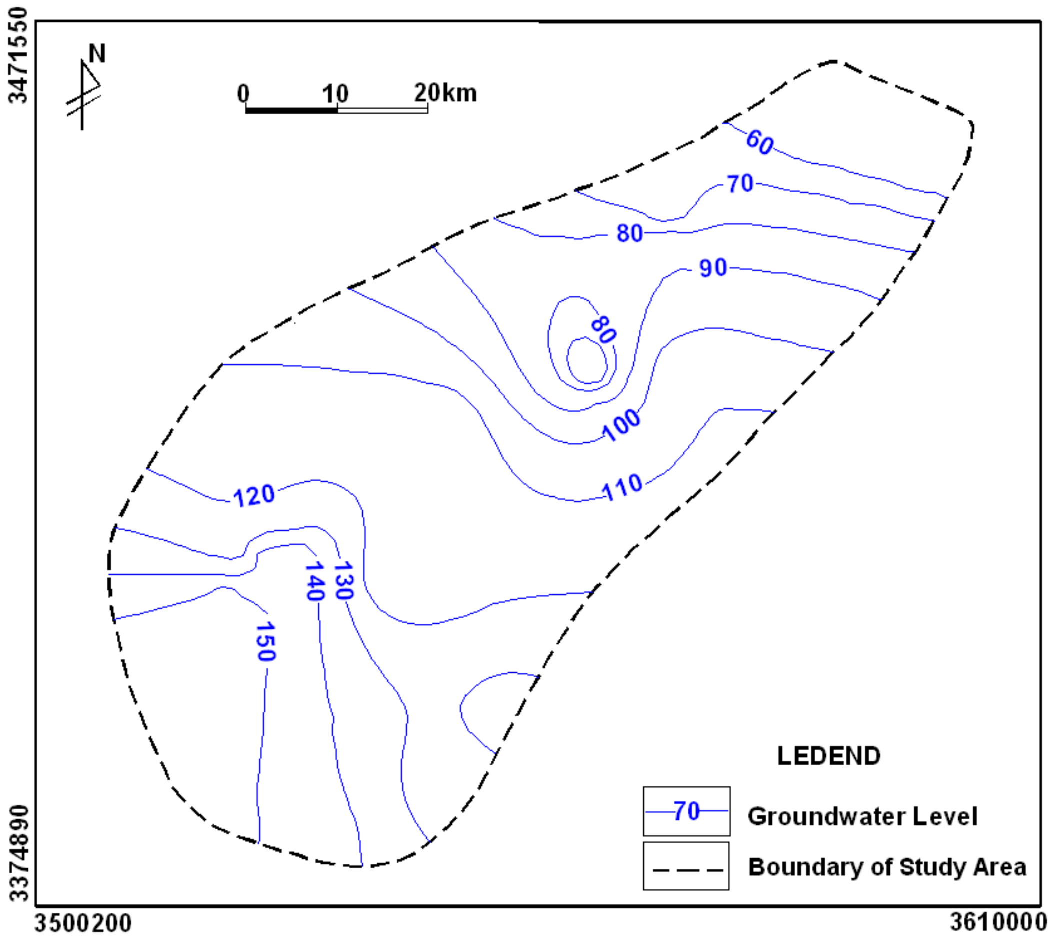

Figure 6.10 initial heads contour of deep groundwater

6.5.5 Model Calibration

The simulation period covers several wet and dry seasons, so the groundwater level dynamic change is a more complex process influenced by characteristics of aquifer structure, hydrogeologic parameters, boundary conditions, sources and sinks. During the simulation process, the parameters as well as some sources and sinks in the model should be adjusted interactively according to the hydrogeologic conditions and other supplementary information to make the calculated heads accord with the observed heads. Figure 6.11 represents a new partition map of calibrated hydraulic conductivity of shallow groundwater and the values of other parameters after calibration are summarized in Table 6.11~Table 6.13.

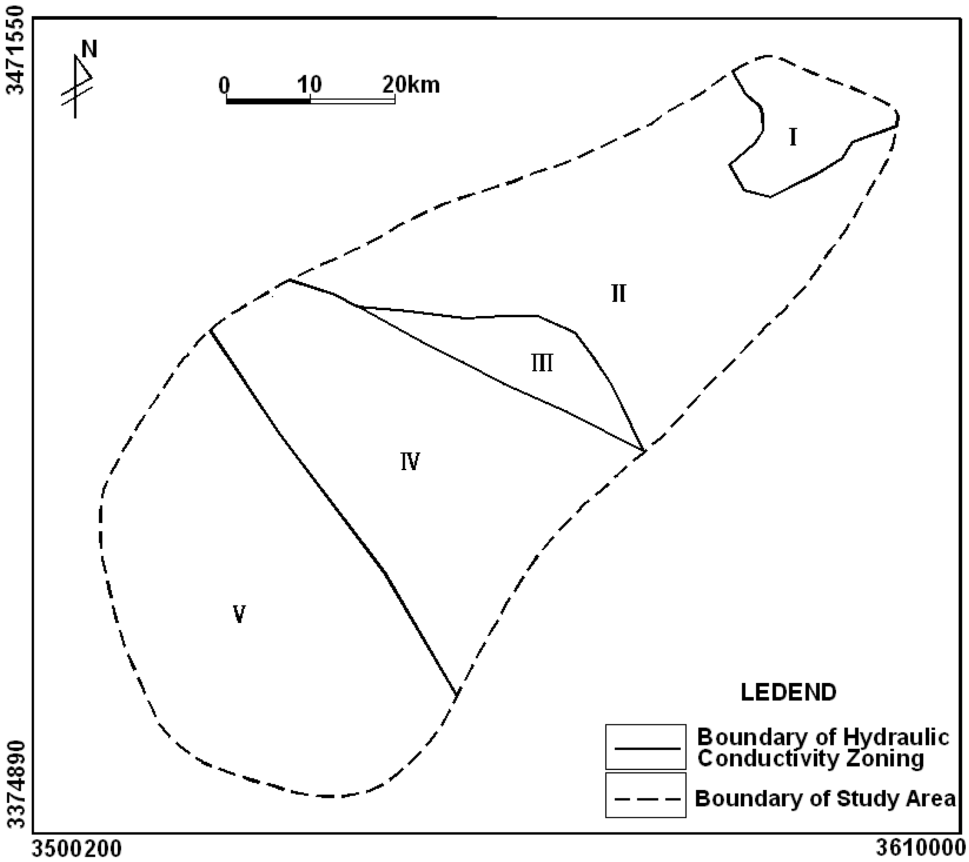

Figure 6.11 Partitions of hydraulic conductivity after calibration for shallow aquifer

Table 6.11 Hydraulic conductivity values of shallow groundwater after calibration

Zone ID	I	II	III	IV	V
K（m/d）	3.5	6	4	0.9	4

Table 6.12 Precipitation infiltration coefficients of shallow groundwater

Zone ID	I	II	III	IV
α（m/d）	0.15	0.06	0.03	0.04

Table 6.13 Permeability coefficients for deep groundwater

Zone ID	I	II	III	IV	V
K（m/d）	0.8	0.4	1.9	3.3	0.4

Figure 6.12 and Figure 6.13 illustrate the comparisons of the simulations with

the observed data in shallow and deep groundwater systems. Overall, calculated results show a reasonably good agreement with observed groundwater heads. Hence, this numerical model can present the real conditions of the characteristics of groundwater flow movement, and the parameters in the model were reasonable. Admittedly, poorer match exists in some parts of the area with the following reasons: (1) the observation wells of shallow groundwater in Wadi Bay distributed in a line along the river valley, while more deep groundwater wells located intensively in middle and downstream of study area where the observed heads influenced largely by groundwater exploitation; (2) the available hydrogeological information is so limited for describing a comprehensive view of groundwater.

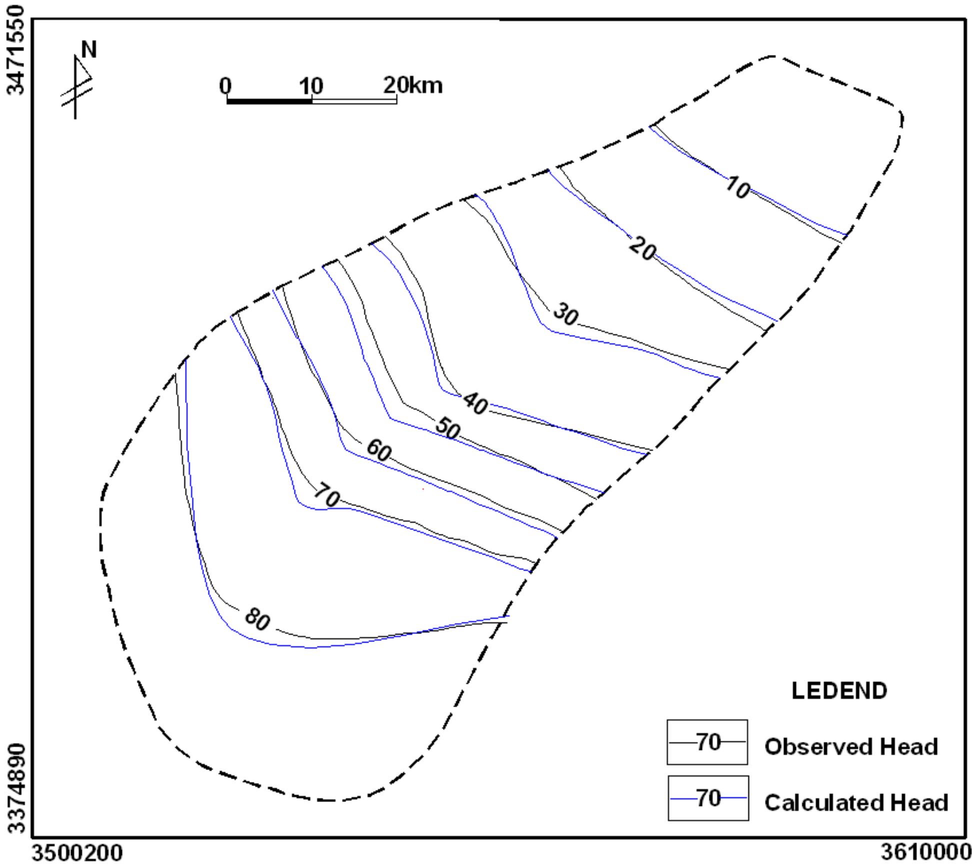

Figure 6.12 Comparison between observed and simulated heads in shallow groundwater

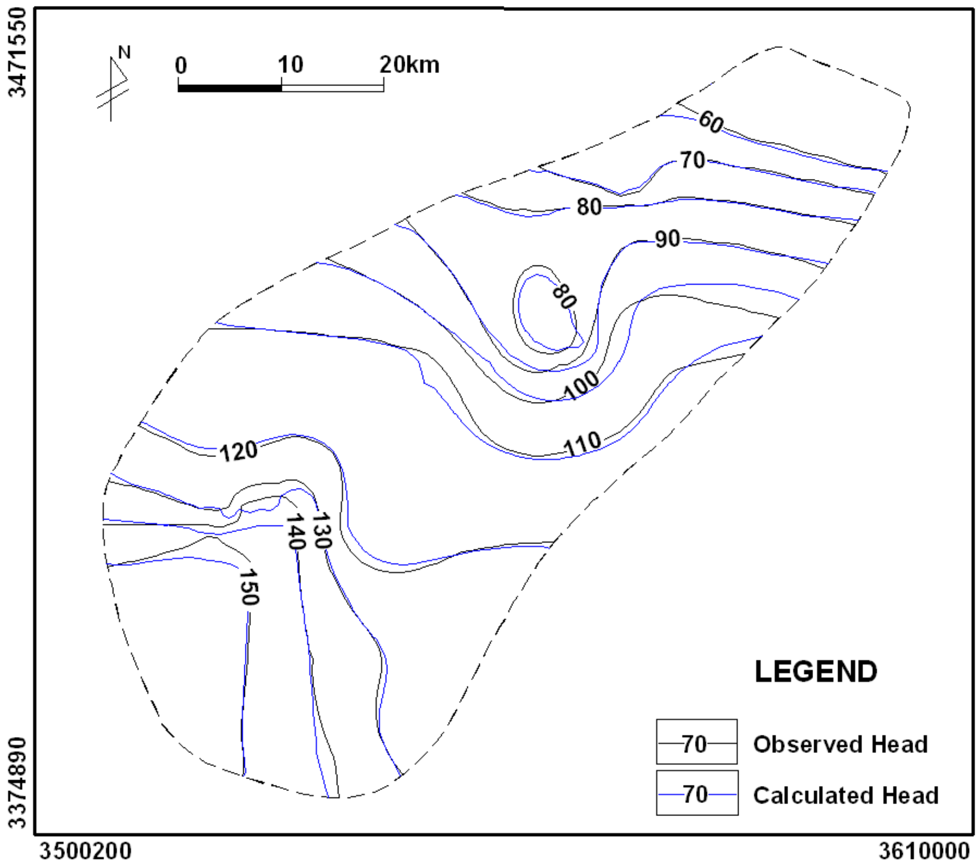

Figure 6.13 Comparison between observed and simulated heads in deep groundwater

6.5.6 Mass Balance

The whole area was divided into several calculated zones in order to study groundwater balance. According to statistic results of ZoneBudget in Visual MODFLOW (Figure 6.14), groundwater balance value of each zone was obtained as shown in Table 6.14. The result of simulated groundwater balance in the modeling area from February 2009 to November 2010 shows that total discharge of shallow and and deep groundwater exceeded total recharge under the current extraction condition. It is considered that Wadi Bay groundwater was in a state of over-exploitation. That is to say if the government keeps pumping groundwater at the current extraction level, groundwater table would continuously decrease.

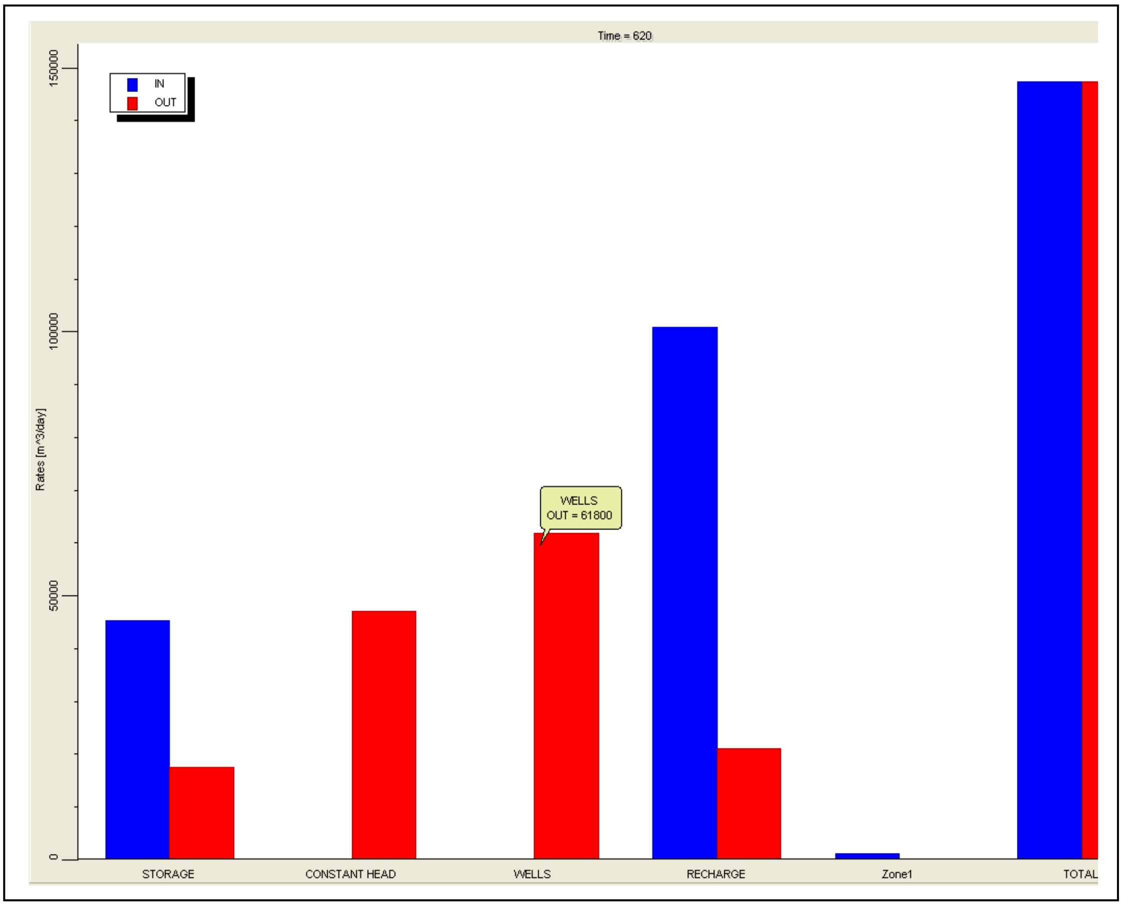

Figure 6.14　Bar graph of shallow groundwater ZoneBudget results at t=620d

Table 6.14　Statistical results of groundwater balance during simulated period

Zone ID		Shallow groundwater	Deep groundwater
Recharge ($10^4m^3/d$)	Lateral runoff	4.98	6.67
	Rainfall infiltration	5.1	-
	Leakage flow	0.06	-
	Total	10.2	6.67
Discharge ($10^4m^3/d$)	Lateral runoff	6.77	3.05
	Exploitation	6.18	5.33
	Leakage flow	-	0.06
	Total	12.95	8.44
Equilibrium difference（$10^4m^3/d$）		-2.75	-1.77

In order to verify whether the result of water balance model is in accordance with the actual conditions, relative error (ΔE) is derived by

$$\Delta E = \frac{|\Delta Q_a - \Delta Q_c|}{\Delta Q_a} \times 100\%$$

where ΔQ_c is the calculated changes of water volume; ΔQ_a is the actual changes of water volume. It is generally considered the precision can be satisfied with ΔE value of no more than 20%.

The equilibrium calculated results (Table 6.15) indicates that both of the ΔE values of shallow and deep groundwater were less than 20%. Therefore, water balance in this model basically accords with the real conditions, and this numerical model can be used for future prediction.

Table 6.15 Comparisons of actual and simulated water balance results

	Shallow Groundwater	Deep Groundwater
ΔQ_c（10^4 m^3/d）	-2.75	-1.77
Range of water level（m）	0.69	1.30
μ (μ*)	0.008	0.0021
ΔQ_a	-3.24	-1.61
ΔE（%）	15.1%	9.9%

6.6 Sensitivity Analysis of Parameters

6.6.1 Overview

As a basic step in groundwater numerical modelling, sensitivity analysis is carried out to understand uncertainty in the calibrated model caused by uncertainties in the estimates of aquifer parameters and stresses. Groundwater models are sensitive to different model input parameters variably and parameters. Sometimes, the model is most sensitive with some parameters, even small changes in those parameters will result in large differences in simulated heads or fluxes. In that case, the simulation results are doubtful and the model should be checked with the parameter determination.

On the other hand, hydrogeologic conditions in Wadi Bay were simplified analyzed in the groundwater numerical simulation and some parameters were determined according to empirical values, which implies many uncertainty in the numerical model.

Therefore, it is necessary to use sensitivity analysis to assess the effects of the uncertain parameters, thereby to increase the reliability of the simulation and prediction for the further studies.

6.6.2 Approaches to Sensitivity Analysis

Sensitivity analysis could be divided into local and global types. Local sensitivity analysis requires one parameter to be changed while the others are kept to the steady state calibrated value so as to check the effect of this parameter to the whole modeling results. To date, the local sensitivity analysis is widely applied in numerical modeling, but there still are limitations such as neglect of interactions among different parameters. By contact with local sensitivity analysis, interactions among different parameters are taken into account in the global sensitivity analysis. However, its calculation progress is more complicated, which limits its application.

By comparing these two methods, local sensitivity analysis is considered more suitable in this study. The formula of sensitivity coefficient is derived as follows:

$$\beta_{i,k} = \frac{\partial H_i}{\partial \alpha_k}$$

where $\beta_{i,k}$ is sensitivity coefficient; H_i is water head at the point of i; α_k is the kth uncertain parameter.

In order to compare effect of different parameters with different units, the formula is then changed to:

$$\beta_{i,k} = \frac{\partial H_i}{\partial \alpha_k} / \frac{H_i}{\alpha_k}$$

The higher the value, the greater influence to the modelling results.

6.6.3 Analysis of Parameter Sensitivity and Modelling Results

The responses of the calibrated numerical model to changes in model parameters like hydraulic conductivity, precipitation infiltration coefficient and specific yield of aquifer were examined. The magnitude of changes in heads from the calibrated solution was used as a measure of the sensitivity of the model to that particular parameter.

1) Shallow Aquifer

The calibrated values of hydraulic conductivity, specific yield and precipitation infiltration coefficient were varied by 10% & 20% increases and decreases at different times to test the sensitivity of the model to the parameters (Table 6.16~Table 6.18). A total of fifteen model runs have been made by changing the each parameter by the specified percents and the groundwater level changes from the calibrated value are shown in Figure 6.15.

Table 6.16 Values of hydraulic conductivity in sensitivity analysis for shallow aquifer

Simulation	**Input values (m/d)**				
	I	**II**	**III**	**IV**	**V**
1	2.8	4.8	3.2	0.72	3.2
2	3.15	5.4	3.6	0.81	3.6
3	3.5	6	4	0.9	4
4	3.85	6.6	4.4	0.99	4.4
5	4.2	7.2	4.8	1.08	4.8

Table 6.17 Values of specific yield in sensitivity analysis for shallow aquifer

Simulation	1	2	3	4	5
Values	0.0064	0.0072	0.008	0.0088	0.0096

Table 6.18 Values of precipitation infiltration coefficient in sensitivity analysis for shallow aquifer

Simulation	Input values			
	I	II	III	IV
1	0.12	0.048	0.024	0.032
2	0.135	0.054	0.027	0.036
3	0.15	0.06	0.03	0.04
4	0.165	0.066	0.033	0.044
5	0.18	0.072	0.036	0.048

According to Figure 6.15, changes in groundwater table can be induced by increases or decreases in hydraulic conductivity, precipitation infiltration coefficient and specific yield. Specifically, equal percentage change in these three parameter values has resulted in more change in groundwater head in case of hydraulic conductivity than others. This shows that the model is most sensitive to hydraulic conductivity, followed by specific yield, and least to infiltration coefficient.

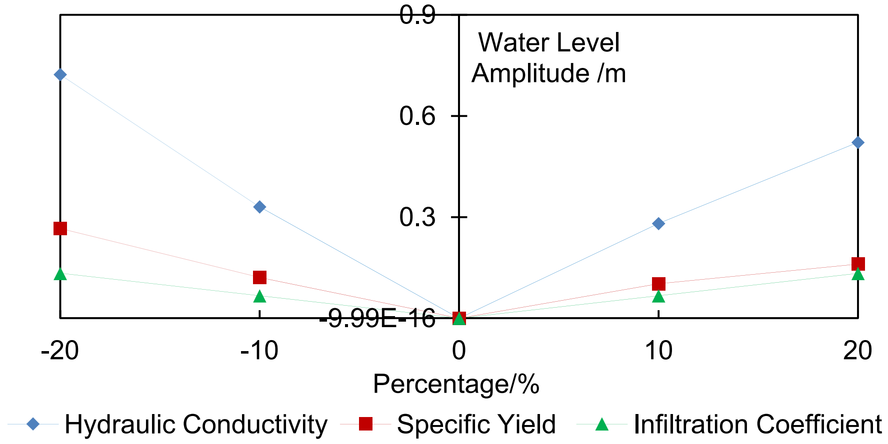

Figure 6.15 Sensitivity analysis results for shallow aquifer

2) Deeper Aquifer

Similarly, sensitivity test was carried out to observe the effects of changes in hydraulic conductivity and storage coefficient to the deep aquifer. The calibrated hydraulic conductivity and storage coefficient values were increased and decreased by 10% & 20% (shown in Table 6.19~Table 6.20) and a total of ten model runs have been made to observe the general trend of changes in groundwater head of deep aquifer.

As it can be seen from sensitivity results given in Figure 6.16, changes in both parameters affected groundwater head in a similar fashion, but with different magnitudes. An increase in either parameter resulted in an increased groundwater level and vice-versa.

In general, the Wadi Baye groundwater flow numerical model constructed in this study is most sensitive to changes in hydraulic conductivity. So, emphasis has been given during the calibration process in estimating these parameters because they influence the model result greatly.

Table 6.19 Values of hydraulic conductivity in sensitivity analysis for deeper aquifer

Simulation	Input values（m/d）				
	I	II	III	IV	V
1	0.64	0.32	1.52	2.64	0.32
2	0.72	0.36	1.71	2.97	0.36
3	0.8	0.4	1.9	3.3	0.4
4	0.88	0.44	2.09	3.63	0.44
5	0.96	0.48	2.28	3.96	0.48

Table 6.20 Values of storage coefficient in sensitivity analysis for deeper aquifer

Simulation	1	2	3	4	5
value	0.00168	0.00189	0.0021	0.00231	0.00252

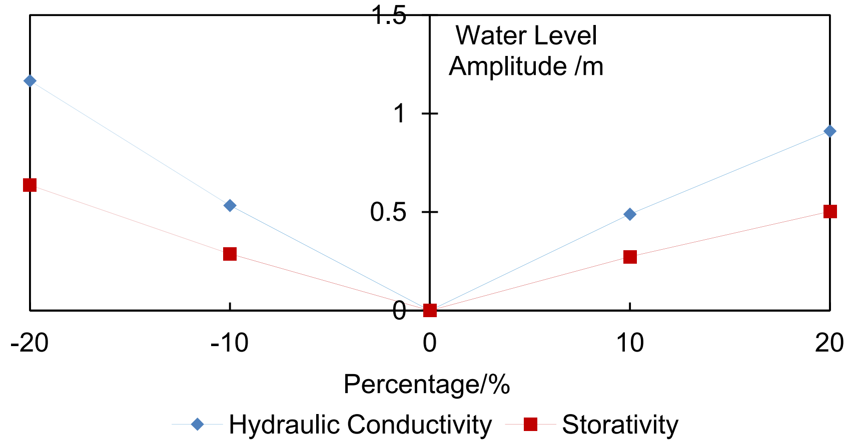

Figure 6.16 Sensitivity analysis results for deeper aquifer

6.7 Summary

The groundwater flow system in the Wadi Bay was described as a conceptual hydrologic model with three lays and of a heterogeneous, isotropy, 3D transient flow. On the basis of the conception model, a numerical model was set up, and the model was calibrated to fit calculated values with observed heads by trial-and-error method.

The results of model were in accordance with the practical hydrogeologic conditions. And the groundwater budget of the study area showed that the total recharge and discharge were $6.67\times10^4m^3/d$ and $8.44\times10^4m^3/d$ with the difference of about $10^4m^3/d$. That indicates aquifers in this area are under a negative balance condition which may get worse if continuous extracting. Additionally, results of relative error in water balance also proved this numerical model is accurate and reasonable enough for future prediction. In the last part, sensitivity analysis of the model indicates the simulated heads are sensitive to hydraulic conductivity, so care has been taken during the calibration of this parameter to which the model was most sensitive.

Chapter 7 FURTHER QUANTITATIVE GROUNDWATER RESOURCES CALCULATION

7.1 Introduction

Quantitative calculation of groundwater resources is not only useful for reasonable exploitation and utilization of the resources but also essential scientific support for groundwater sustainable management. It is considered that the reasonable calculation of groundwater recharge capacity, safe yield and groundwater exploitation potentiality is critically important for the sustainable utilization of regional groundwater resources in Libya under such an arid climate.

7.2 Calculation of groundwater recharge

Groundwater recharge refers to the water that enters the aquifer system through various channels under natural or artificial interfered conditions. It mainly involves the precipitation infiltration, surface water seepage, underground interflow, groundwater lateral inflow and so on. The plentiful groundwater recharge via various ways and at various times (modern or paleo) warrantees a rich groundwater resource for proper and ample supply.

Recharge of groundwater system in this study area includes the limited precipitation infiltration for shallow groundwater and lateral inflow or leakages from other systems for both the aquifers. In this study the recharge from precipitation was calculated by statistical methods, i.e. frequency analysis specifically, based upon the existing meteorological data.

7.2.1 Precipitation infiltration

The precipitation amount is calculated by the Pearson III frequency analysis curves at the assurance rates P=25%, P=50% and P=75%. According to the data series of precipitation from 4 weather stations in and around study area (Sirte for 1970 ~ 2005, Misurata for 1971 ~ 2005, Abu Njayam for 1994 ~ 2005, Hun for 2000 ~ 2005). The Pearson III curves results are shown in Figure 7.1~Figure 7.3. Values of precipitation at three typical assurance rates were read from these curves, and summarized in Table 7.1. Then distributions of precipitation amount at different assurance rates of study area are obtained as shown in Figure 7.4~Figure 7.7.

Table 7.1 Precipitation at different assurance rates in each weather station

P	Precipitation (mm)			
	Misurata	Sirt	Abu Njayam	Hun
25%	342	243	31.3	—
50%	275	185	21.0	—
75%	216	139	12.2	—
Average	281.8	198.5	22.7	24.7

Note: For the weather station of Hun, frequency analysis was not done because of lacking data series.

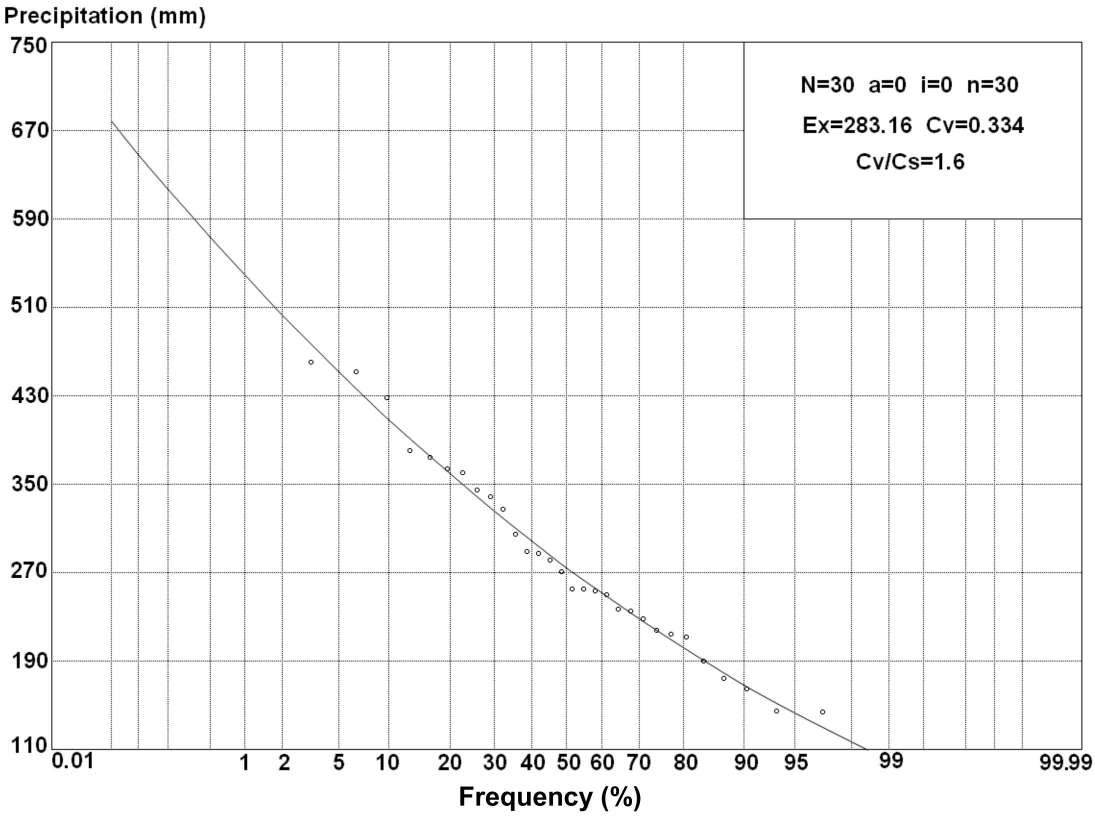

Figure 7.1 Pearson III frequency curve of precipitation at Misurata

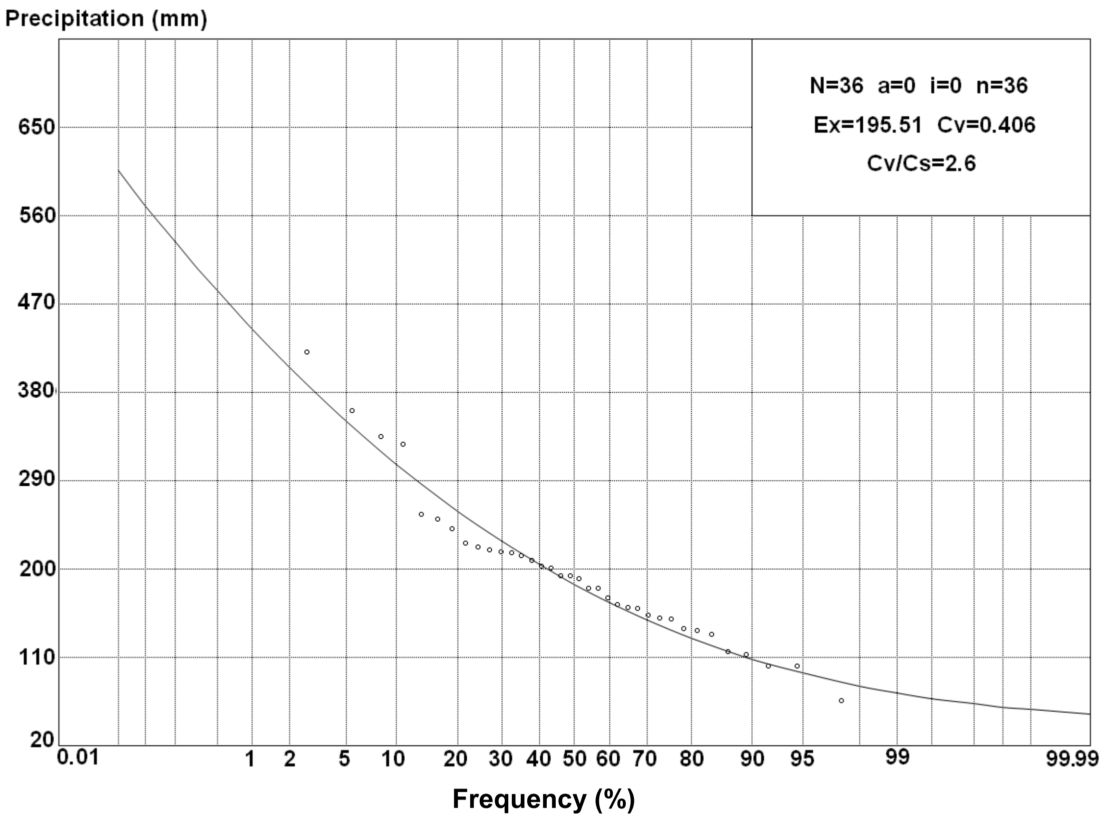

Figure 7.2 Pearson III frequency curve of precipitation at Sirte

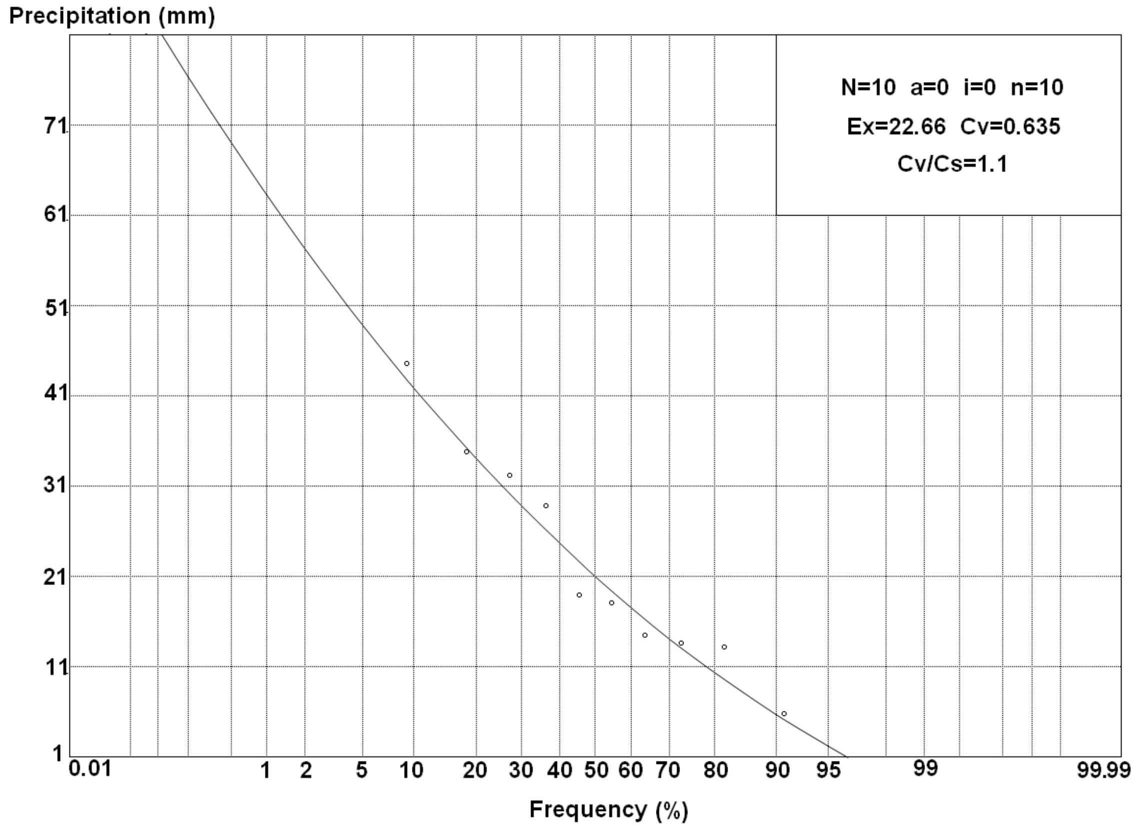

Figure 7.3 Pearson III frequency curve of precipitation at Njayam

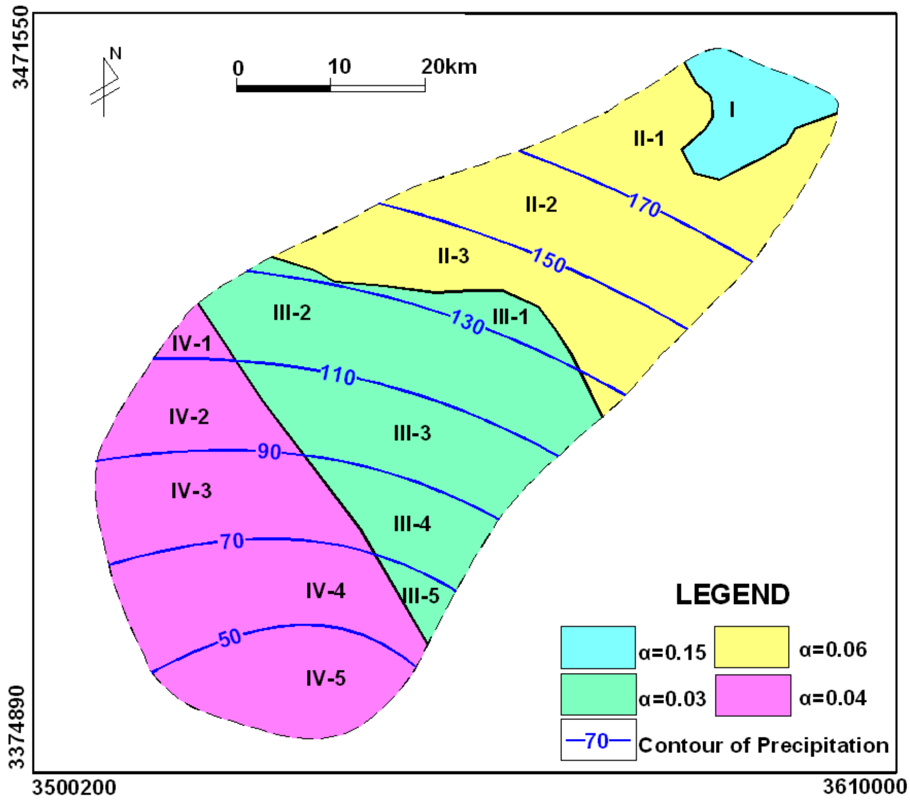

Figure 7.4 Distribution of precipitation at the assurance rate P=25%

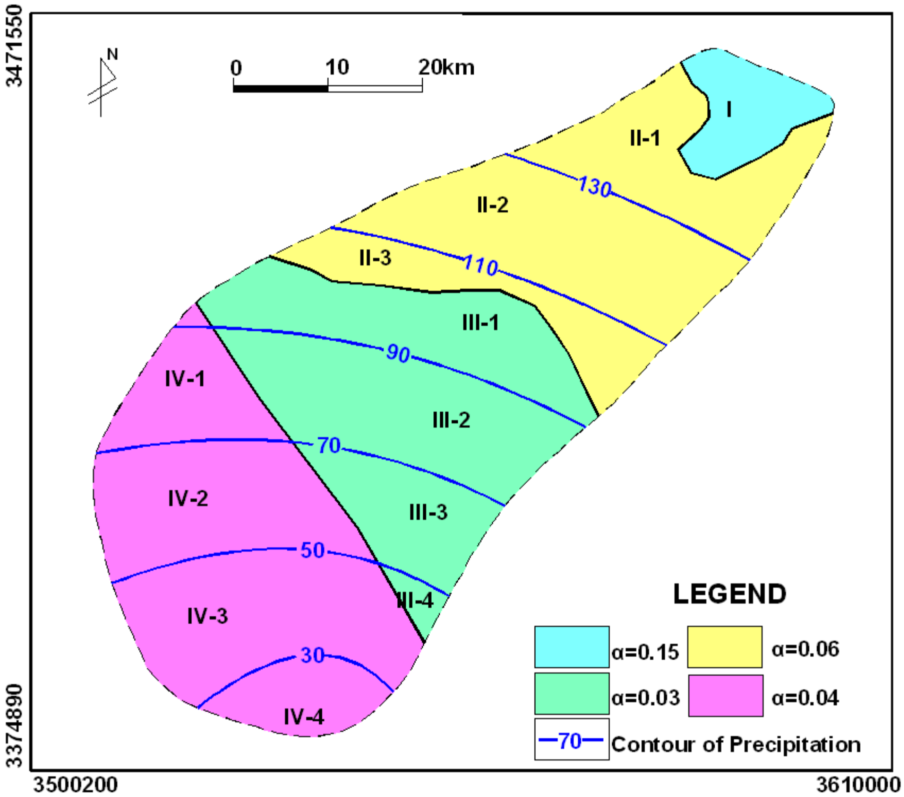

Figure 7.5 Distribution of precipitation at the assurance rate P=50%

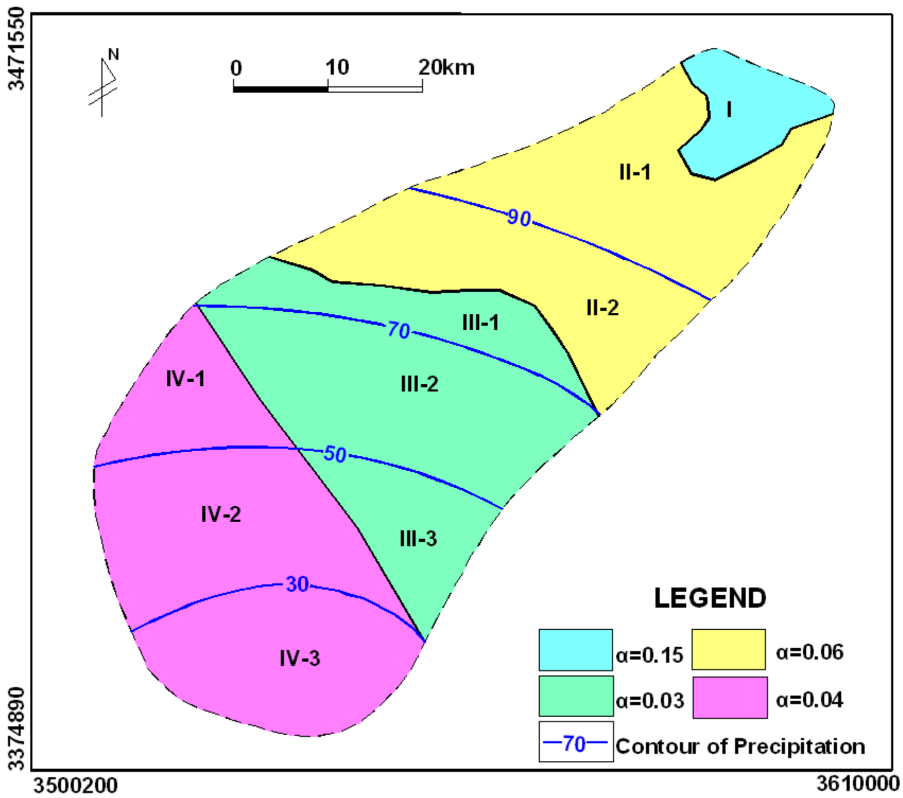

Figure 7.6 Distribution of precipitation at the assurance rate P=75%

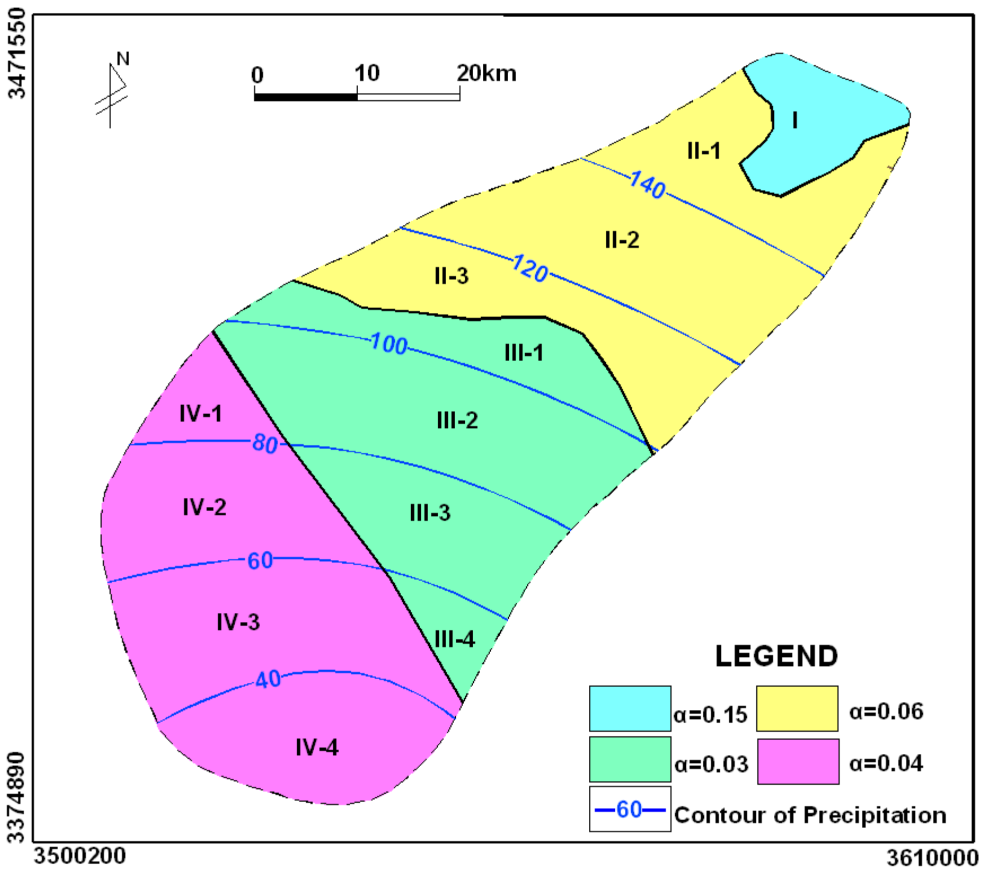

Figure 7.7 Distribution of calculated average annual precipitation

The zonation of the recharge calculation here was taken as the same as previous calculation in Chapter 6, decided according to structures (e.g. faults), lithology, stratigraphy and land uses (cir. Figure 6.5).

Therefore, precipitation infiltration of zones in this area was derived from the following equation:

$$Q_p = F \times \alpha \times X \times 1000$$

where Q_p is precipitation infiltration amount (m^3/a); α is infiltration coefficient; F is study area (km^2); X is annual precipitation (mm); and 1000 a unit conversion factor. Results are summarized in Table 7.2.

Table 7.2 The calculation results of precipitation infiltration

P	Zone ID	F (km^2)	X (mm)	α	Q_p (m^3/d)	Total (m^3/d)
25%	I	167	190	0.15	13039.73	61608.05
	II-1	345.0644	180	0.06	10210.12	
	II-2	392.9693	160	0.06	10335.63	
	II-3	381.9664	140	0.06	8790.459	
	III-1	97.11134	140	0.03	1117.446	
	III-2	481.2931	120	0.03	4747.001	
	III-3	332.7403	100	0.03	2734.852	
	III-4	174.5114	80	0.03	1147.472	
	III-5	40.34382	60	0.03	198.9558	
	IV-1	34.3691	120	0.04	451.9773	
	IV-2	195.9192	100	0.04	2147.059	
	IV-3	324.8953	80	0.04	2848.397	
	IV-4	387.8889	60	0.04	2550.502	
	IV-5	293.9276	40	0.04	1288.45	
50%	I	167	150	0.15	10294.52	47161.15
	II-1	353.5108	140	0.06	8135.591	
	II-2	523.4265	120	0.06	10325.12	
	II-3	243.0628	100	0.06	3995.552	
	III-1	366.885	100	0.03	3015.493	
	III-2	504.0922	80	0.03	3314.579	
	III-3	224.3461	60	0.03	1106.365	
	III-4	30.67667	40	0.03	100.8548	
	IV-1	205.335	80	0.04	1800.197	
	IV-2	403.0044	60	0.04	2649.892	
	IV-3	476.8231	40	0.04	2090.183	
	IV-4	151.8375	20	0.04	332.7945	

Table 7.2 The calculation results of precipitation infiltration (Continued)

P	Zone ID	F (km^2)	X (mm)	α	Q_p (m^3/d)	Total (m^3/d)
75%	I	167	110	0.15	7549.315	34711.99
	II-1	590.6926	100	0.06	9710.015	
	II-2	529.3074	80	0.06	6960.755	
	III-1	253.9131	80	0.03	1669.566	
	III-2	631.686	60	0.03	3115.164	
	III-3	240.4009	40	0.03	790.3592	
	IV-1	231.6077	60	0.04	1522.9	
	IV-2	543.0834	40	0.04	2380.64	
	IV-3	462.3089	20	0.04	1013.28	
Average	I-1	167	170	0.15	11667.12	50965.72
	II-1	321.7772	150	0.06	7934.231	
	II-2	490.4979	130	0.06	10481.87	
	II-3	307.725	110	0.06	5564.342	
	III-1	242.3166	110	0.03	2190.808	
	III-2	539.9354	90	0.03	3994.043	
	III-3	265.4763	70	0.03	1527.398	
	III-4	79.51052	50	0.03	326.7556	
	IV-1	109.4628	90	0.04	1079.633	
	IV-2	339.5521	70	0.04	2604.783	
	IV-3	456.5321	50	0.04	2501.546	
	IV-4	332.5108	30	0.04	1093.186	

7.2.2 Groundwater lateral inflow

The inflow rate of aquifers through the lateral boundary was calculated by

$$Q_L = K \cdot I \cdot B \cdot M \cdot \Delta T \cdot \sin\theta$$

where Q_L is groundwater lateral inflow rate (m^3/d); K is hydraulic conductivity (m/d); I is groundwater hydraulic gradient; B is width of cross section (m); M is aquifer thickness (m); ΔT is calculated time (d); θ is the angle between groundwater flow and cross section.

Cross-sections division of aquifers is the same as that in the numerical model (shown in Figure 6.6 and Figure 6.7). In fact, hydraulic gradient at the boundary may change in case of precipitation or artificial pumping. However, changes were hardly quantified due to the limited data, so results in current year were used in the future predictions. Table 7.3 represents the lateral inflow rates through different cross sections and other data of parameters in the calculation which were derived from the numerical model.

Table 7.3 The calculation results of groundwater lateral runoff recharge

Aquifer	Cross section ID	$B \cdot M$ ($10^4 m^2$)	sinθ	I	K (m/d)	Q_L (m^3/d)	Total (m^3/d)
Shallow aquifer	D-E	328.76	0.56	0.0007	4.0	5155.02	49784.21
	E-F	544.88	0.70	0.00056	4.0	8543.734	
	F-G	299.92	0.51	0.00045	4.0	2753.302	
	G-H	603.65	0.18	0.0021	0.9	2053.621	
	H-I	679.68	0.38	0.0013	6.0	20145.57	
	I-J	643.90	0.38	0.0013	3.5	11132.97	
Deep aquifer	E-F	568.89	0.76	0.0014	0.8	4842.392	66611.75
	D-E	147.82	0.07	0.0024	0.8	198.6764	
	G-H	144.50	0.83	0.0017	3.3	6728.354	
	H-I	569.14	0.73	0.004	3.3	54842.33	

7.2.3 Total groundwater recharge

The total recharge of shallow aquifer is the sum of the precipitation infiltration and groundwater inflow, while that of deep aquifer only contains groundwater lateral inflow. The recharge for the whole area equals to the sum of all the above.

Table 7.4 The calculation results of total groundwater recharge

P	**Shallow aquifer**		**Deep aquifer**	**Total (m^3/d)**
	Q_P (m^3/d)	**Q_L (m^3/d)**	**Q_L (m^3/d)**	
25%	61608.05	49784.21	66611.75	178004.05
50%	47161.15	49784.21	66611.75	163557.11
75%	34711.99	49784.21	66611.75	151107.95
Average	50965.72	49784.21	66611.75	167361.68

As shown in Table 7.4, the groundwater recharge varies with the assurance rate (*P*). The maximum groundwater recharge occurs in the rainy year (P=25%), and the minimum in the dry year. Besides, the precipitation at different assurance rates changes larger in northern coast, and changes smaller in southern inland plains. So the increased recharge is mainly the precipitation infiltration recharge at the northern coast.

7.3 Quantification of groundwater resources

7.3.1 groundwater lateral outflow

The amount of natural lateral outflow is the major discharge of the shallow and deep aquifers in study area. For the whole area, outflow occurs just at the boundary with hydraulic gradient toward the outside. Calculation of the lateral outflow is the same as that of inflow in 7.2.2. The results are shown in Table 7.5. Thereby, the total natural discharge is equal to the sum of shallow and deep aquifers, that being 98238.01 m^3/d.

Table 7.5 The lateral outflow rate of groundwater system

Aquifer	Cross-section ID	$B \cdot M$ ($10^4 m^2$)	sinθ	I	K (m/d)	Q_L (m^3/d)	Total (m^3/d)
Shallow aquifer	A-B	523.28	0.37	0.0012	3.5	8131.709	67737.65
	B-C	508.10	0.37	0.0011	6	12407.802	
	C-D	363.92	0.09	0.0019	0.9	560.06519	
	J-A	572.39	0.97	0.0024	3.5	46638.068	
Deep aquifer	A-B	262.30	0.37	0.0024	3.3	7686.439	30500.36
	B-C	529.94	0.95	0.0026	0.4	5235.787	
	C-D	168.48	0.51	0.0022	0.4	756.116	
	F-G	221.36	0.71	0.0012	1.9	3583.376	
	I-A	299.30	0.97	0.0057	0.4	13238.64	

7.3.2 Calculation of storage capacity

Storage refers to the volume of gravity water which is stored in water-bearing media at some time. The storage capacity in unconfined aquifer is called volume storage which can be derived as follows:

$$W_v = \mu V$$

where W_v is the storage capacity of unconfined aquifer (m^3); V is the volume of unconfined aquifer (m^3); μ is the specific yield.

Except for the volume storage, the confined aquifer contains elastic storage, and its calculation formula is:

$$W_s = FSh$$

where W_s is the elastic storage of confined aquifer (m^3); F is the area of aquifer (m^2);S is storage coefficient; h is the pressure head above the top of confined aquifer. The hydrogeological parameters and other data are from previous chapters as we discussed earlier sections. Table 7.6 and Table 7.7 present the calculation results of shallow and deep aquifers respectively.

Table 7.6 The storage capacity of groundwater in shallow aquifer

μ	Aquifer volume(10^8m^3)	Storage capacity(10^8m^3)
0.008	17235.6	137.88

Table 7.7 The storage capacity of groundwater in deep aquifer

Area(10^8m^2)	Storage coefficient	Average hydraulic head (m)	Storage capacity (10^8m^3)
36.5	0.0021	1310.3	100.43

7.3.3 Estimation of safety yield

Safety yield is the term used to express the amount of water an aquifer or well can yield for consumption without producing unacceptable negative effects. It is usually equal to the average replenishment rate of the aquifer, which can be derived from conservation of mass principles in a groundwater basin as follows:

$$Q_S = Q_R - Q_D$$

where Q_R is the amount of recharge; Q_D is the amount of natural discharge; Q_S is safety yield.

According to the above equation, safe yield was estimated, and the results of calculation were shown in Table 7.8. Investigation of groundwater exploitation in Wadi Baye indicates current pumping rate is largely exceeded the safe yield, which will lead to the overexploitation and groundwater level decrease.

Table 7.8 Safe yield of aquifers in the study area

Aquifer	P	Q_R ($10^4 m^3/d$)			Q_D ($10^4 m^3/d$)		Q_S ($10^4 m^3/d$)
		Precipitation infiltration	Lateral runoff	Leakage flow	Lateral runoff	Leakage flow	
Shallow aquifer	25%	6.16	4.98	0.06	6.77	—	4.43
	55%	4.71	4.98	0.06	6.77	—	2.98
	75%	3.47	4.98	0.06	6.77	—	1.74
	Average	5.10	4.98	0.06	6.77	—	3.37
Deep aquifer	—	—	6.67	—	3.05	0.06	3.56

Note: The amount of leakage flow was adopted the statistical result of model.

7.3.4 Potentiality of groundwater exploitation

Potential evaluation of groundwater exploitation can help to investigate the differences of sustainable exploitation between current and ideal situation of water resources exploitation, and provide rational advises for groundwater development. The potentiality of groundwater exploitation is measured by the exploitation potentiality index (*EPI*) is calculated by formula:

$$EPI=Q_S/Q_C$$

where Q_S is the safe yield (m^3/a); Q_C is the current exploitation quantity (m^3/a). The classification criteria of *EPI* are described in Table 7.9.

Table 7.9 Grading standard of exploitation potentiality index

EPI	Exploitation degree	Descriptions
>1.4	Lower	The exploitation can be expanded
1.2~1.4	Low	The exploitation can be expanded moderately
0.8~1.2	Balance	The exploitation can be maintained
0.6~0.8	Overexploitation	The exploitation should be controlled moderately
<0.6	Overexploitation severely	The exploitation should be controlled severely

According to the above equation, the results of exploitation potential index for aquifers in this area were derived as shown in Table 7.10. As can be seen from it, the *EPI* values of shallow aquifer are less than 0.8 with the minimum of 0.28 in dry year and the maximum of 0.72 in rainy year (P=25%). That indicates groundwater has been severely overexploited. Thus, the groundwater resources of shallow aquifer don't have the ability for increasing exploitation unless more recharge can be induced from adjacent areas. Moreover, the EPI value of deep aquifer is just 0.67, which indicates water pumping greatly exceeds the safe yield in deep aquifer. Groundwater level will continues to decline and the depression cone of groundwater level will expand gradually under current exploitation condition.

In summary, actions must take to control groundwater pumping to prevent the situation from getting worse, and the scientific and rational exploitation strategy should be undertaken in order to maintain the groundwater sustainable utilization at a regional/ catchment scale. This is to utilise the dynamic resource at a spatial scale to optimise the development for sustainability, which is particularly useful for a country like Libya.

Table 7.10 Exploitation potentiality indices of aquifers

Aquifer	P	Q_C ($10^4m^3/d$)	Q_S ($10^4m^3/d$)	*EPI*
Shallow aquifer	25%	6.18	4.43	0.72
	50%	6.18	2.98	0.48
	75%	6.18	1.74	0.28
	Average	6.18	3.37	0.55
Deep aquifer	—	5.33	3.56	0.67

7.4 Scenario Analysis of Groundwater Utilization

Based well done calibrations, numerical models are widely used to predict and compare the variation of water quantity and groundwater flow under different scenarios, so as to present reasonable strategy for groundwater development.

7.4.1 Scenarios Design

Pumping scenarios were chosen to test the response of the system under variable groundwater withdrawal rates. System response was evaluated by using fluxes and heads of the calibrated model as a baseline. The system response was compared with resulting changes in water table elevation. Three scenarios of different groundwater withdrawals were proposed in this study (Table 7.11).

Scenario 1: With rapid growth of population and fast development both in industry and agriculture, more and more water was exploited to meets various demands, which makes the severe confliction between recharge and discharge. The current exploitation rate is increasing with the rate of 2% per year, thereby scenario 1 is proposed under this situation with the pumping rate of each year shown in Table 7.12.

Scenario 2: The pumping rate maintains the current value.

Scenario 3: The pumping rate is controlled at the value of safe yield.

Table 7.11 Description of proposed scenarios

Scenarios	Design of exploitation scheme	Amount of Precipitation
1	Increasing pumping by 2% per year	Average amount of precipitation
2	Current pumping rate	
3	Decreasing pumping to the safe yield	

Table 7.12 Pumping rates in scenario 1

Year	**Pumping rate (m^3/d)**	
	Deeper aquifer	**Shallow aquifer**
2011	53315	61800
2012	54381	63036
2013	55469	64297
2014	56578	65583
2015	57710	66894
2016	58864	68232
2017	60041	69597
2018	61242	70989
2019	62467	72409
2020	63716	73857

7.4.2 Prediction Results

1) Scenario 1

The predication results are illustrated in Figure 7.8~Figure 7.11. As the results shown that groundwater table in shallow aquifer wells is decreasing, and the decrease scopes in the central region are smaller than those in the western region. The results also indicate that the regional groundwater level will decline by 7.04m till 2020 with drawdown rate of 0.704m/a, but the flow will maintain the same direction. The similar conclusion could be drawn in the deep aquifer under the overexploitation for a long period. The drawdown will be 14.42m till 2020. The scope of depression cone in the central region will increase with a new one occurring in the southern region.

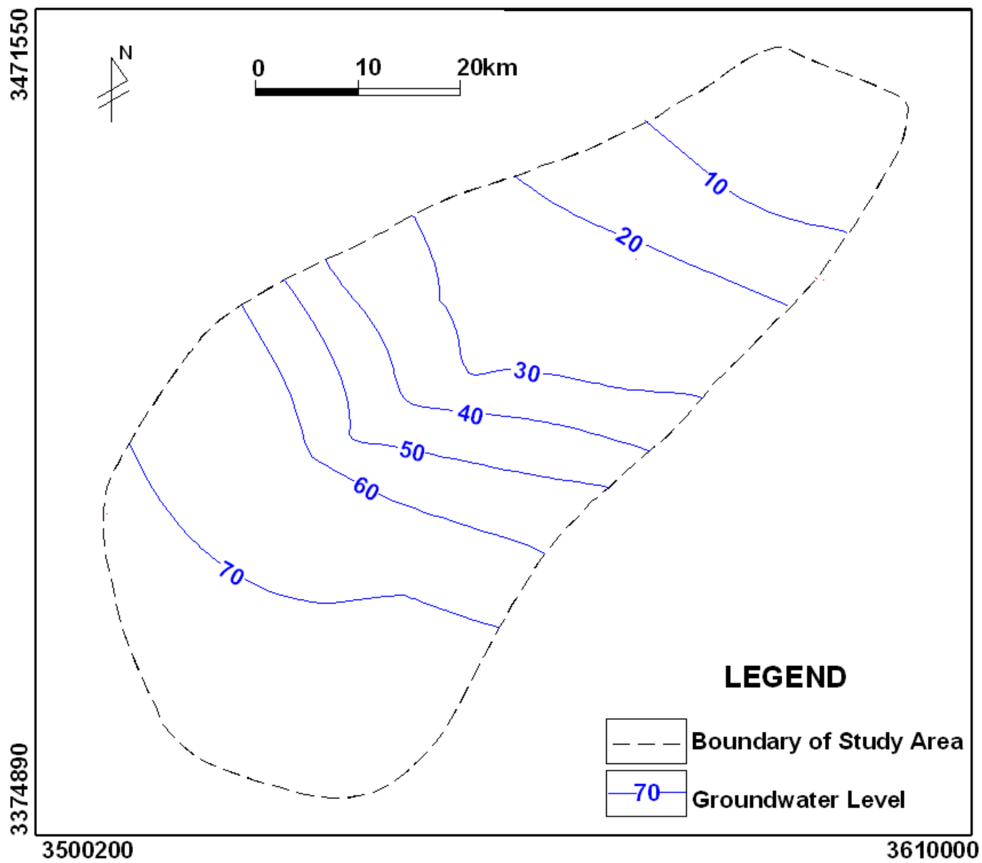

Figure 7.8 Groundwater level (MaD) in 2020 for shallow aquifer under Scenario 1

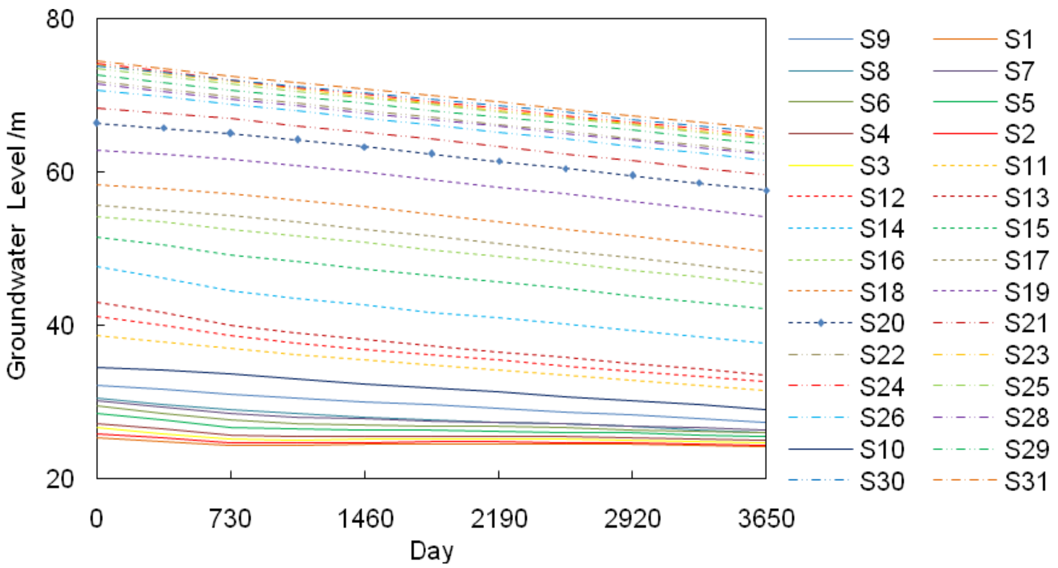

Figure 7.9 Temporal variations of groundwater level for shallow aquifer in Scenario 1

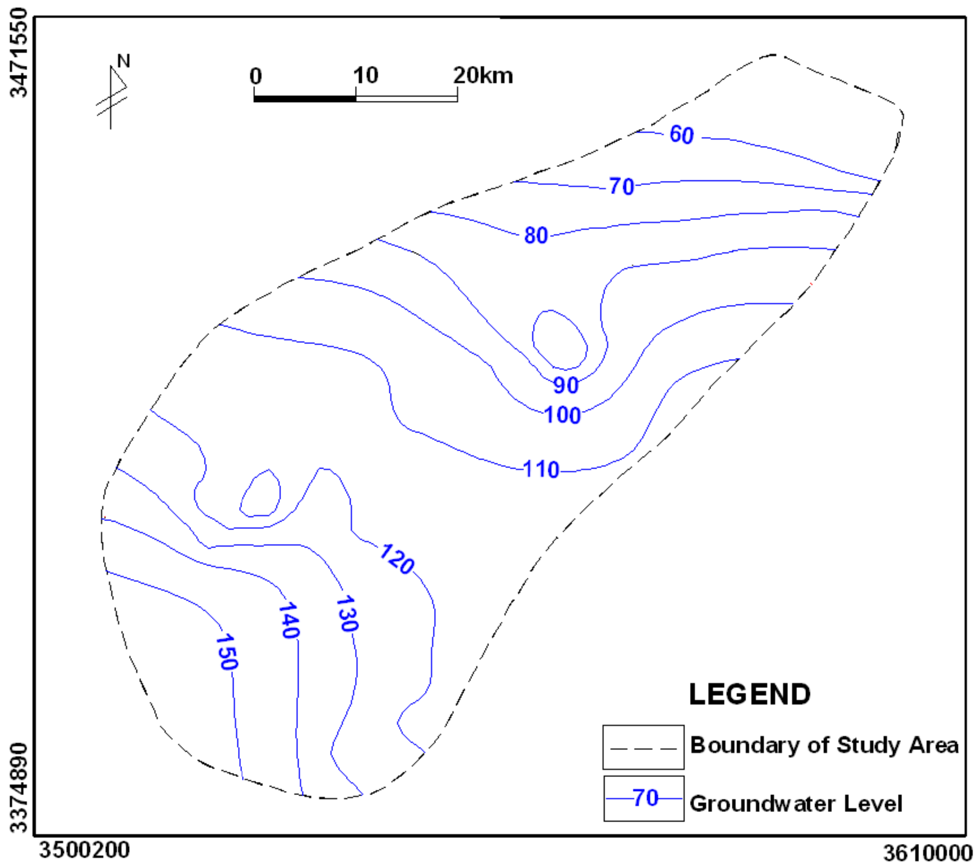

Figure 7.10 Groundwater level (MaD) in 2020 for deep aquifer under Scenario 1

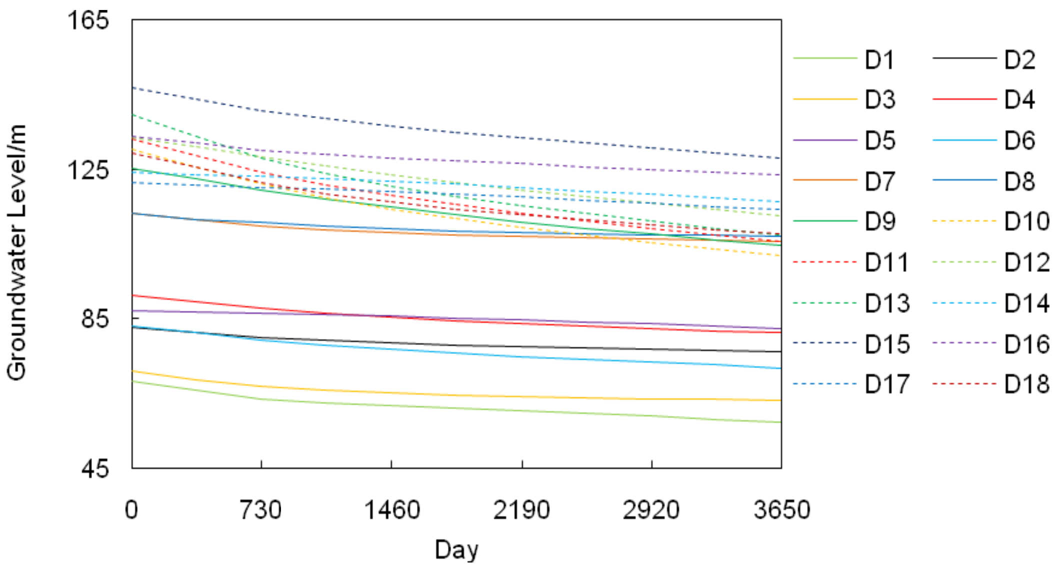

Figure 7.11 Temporal variations of groundwater level for deep aquifer in Scenario 1

These figures (Figures 7.8 and 10) show the predicted spatial distributions of the groundwater table in meter above datum (MAD) in 2020; and Figure 7.9 and 11 present the temporal variations of groundwater table (also MaD) at the observation borehole locations. The curves are quite straight as no detailed planning data varies during the modelling prediction scenario.

2) Scenario 2

In this scenario, the steady pumping rate was set at the current value, namely of 61800 m^3/d for the shallow aquifer and 53315 m^3/d for the deeper aquifer. Model simulated results of the groundwater levels in the scenarios were compared with model calibrated results, and the differences showed the response of the system to the assumed scenarios.

As it shown in Figure 7.13, the groundwater level in shallow aquifer will keep descending while the flow direction will not change under this scenario (Figure 7.12). Specifically, regional average drawdown reaches 5.52m with the maximum value of

8.34m and the minimum of 0.33m. Though groundwater level in deeper aquifer also decreases (Figure 7.15), it is still higher than that in shallow aquifer. There are two reasons for the decline of groundwater level in deep aquifer. Firstly, deeper groundwater discharges to shallow aquifer through the aquitard between them. Secondly, long period exploitation causes the groundwater levels fall increasingly year by year. The consequent is that depression cone in the concentrated pumping area becomes larger and new ones emerge in the southern region as shown in Figure 7.14.

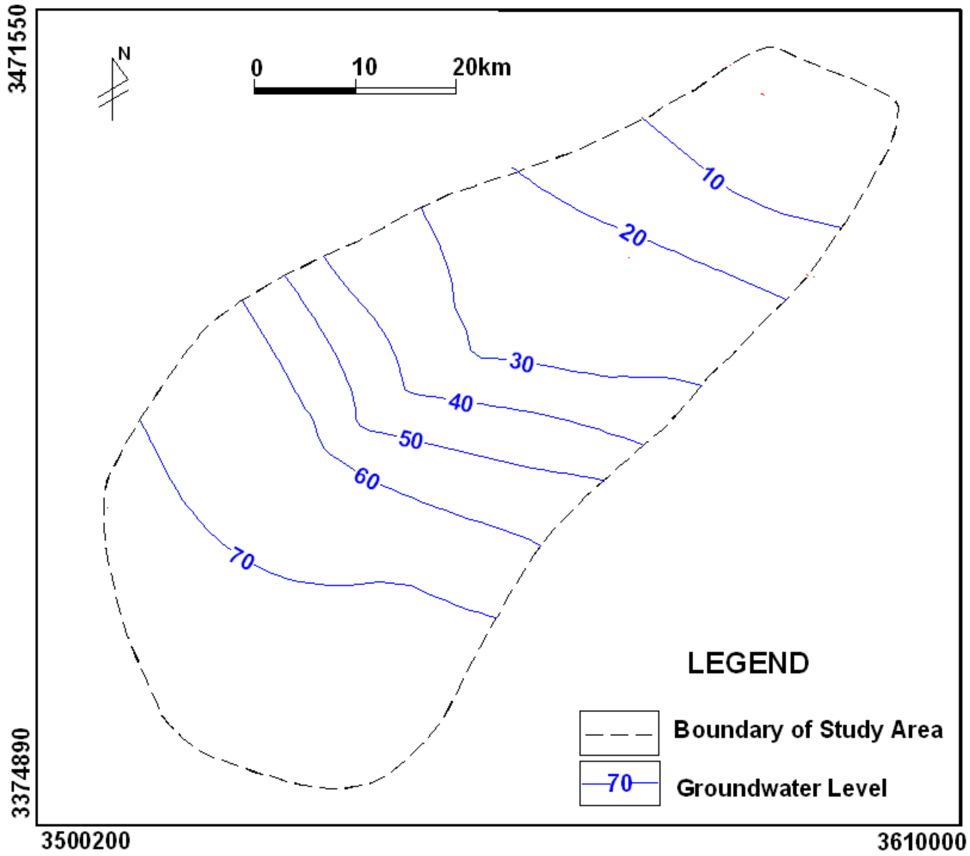

Figure 7.12 Groundwater level in 2020 for shallow aquifer under scenario 2

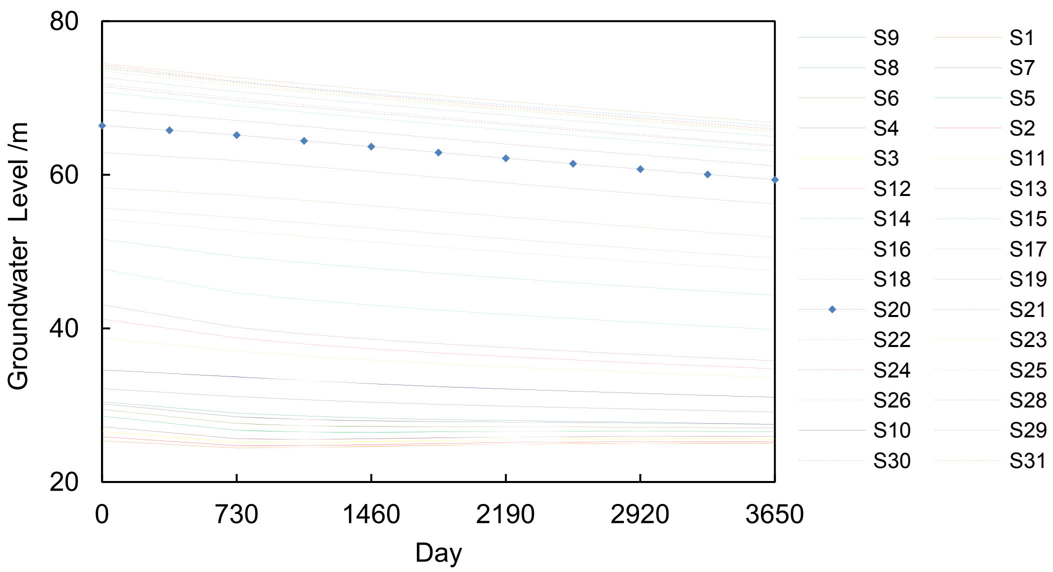

Figure 7.13 Temporal variations of groundwater level for shallow aquifer in scenario 2

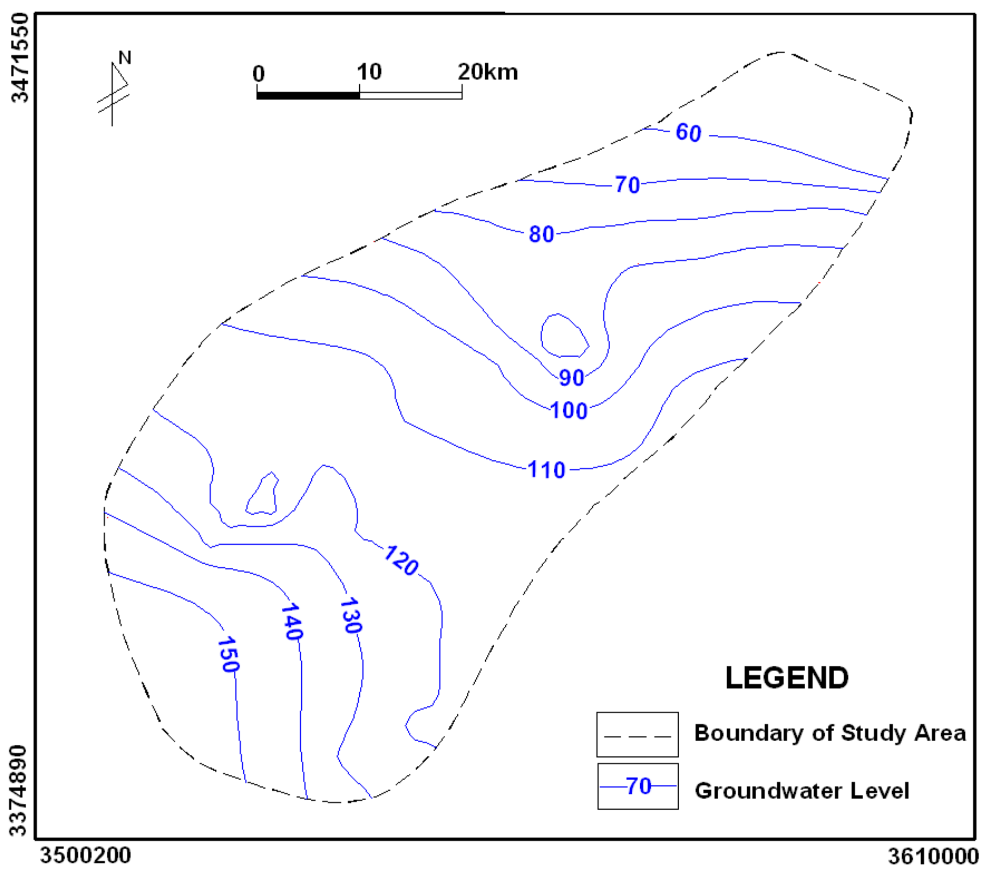

Figure 7.14 Groundwater level in 2020 for deep aquifer under scenario 2

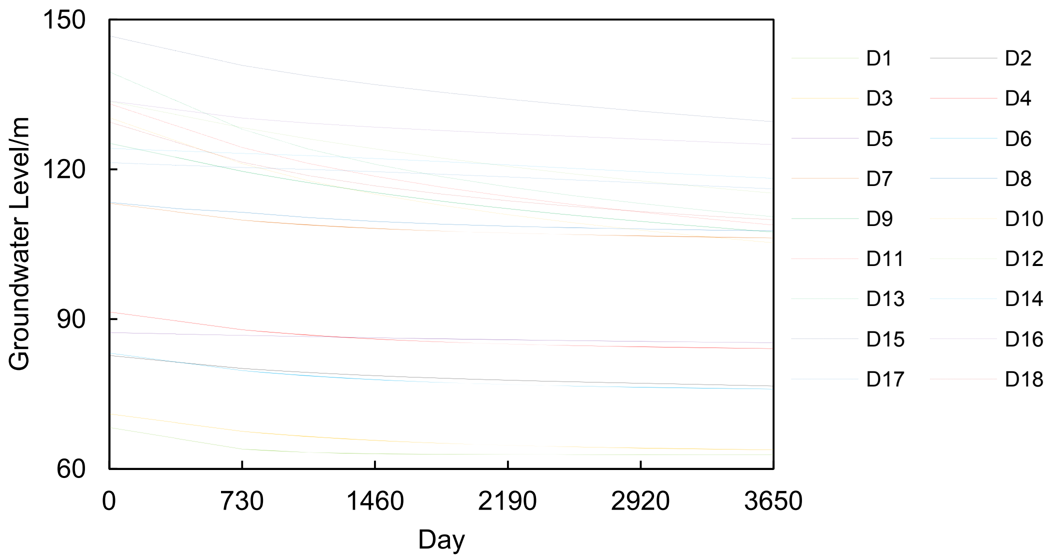

Figure 7.15 Temporal variations of groundwater level for deep aquifer in scenario 2

3) Scenario 3

In this scenario, the steady pumping rate was proposed at the value of safe yield, namely of 33700 m^3/d for the shallow aquifer and 35600 m^3/d for the deeper aquifer. The total withdrawals were distributed as the current proportion among the existing wells. The prediction results are illustrated in Figure 7.16~Figure 7.19.

It could be clear seen that the groundwater table in shallow aquifer stays constant under this scenario. However, an obvious decline in groundwater levels head was found in the southern region, probably due to the concentrated pumping.

The water tables in deeper aquifer wells remained stable over the next 10 years till 2020 according the modelling results of scenario 3. More specifically, groundwater level in most well has a slight rise except for those in the southern region, which is likely to be caused by the same reason as mentioned in the shallow aquifer. So it is obvious that water table changes are mainly affected by the pumping rate. Another proof for this case is that depression cone in the central region has been vanishing since the pumping rate decreases.

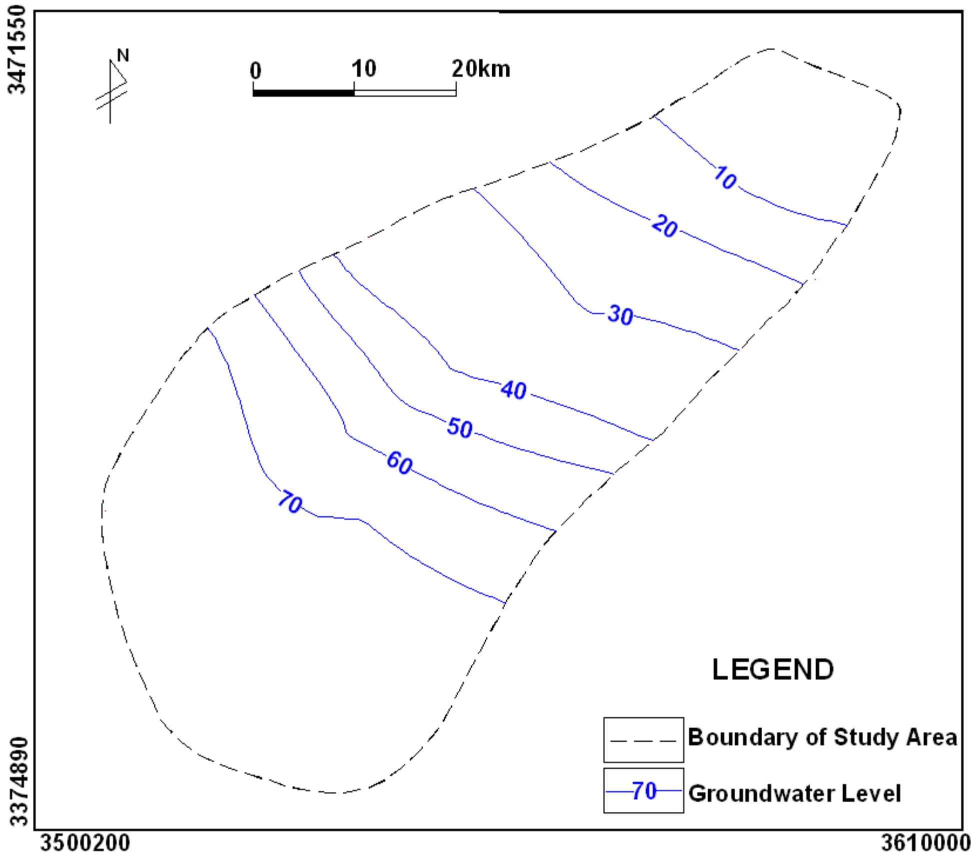

Figure 7.16 Groundwater level in 2020 for shallow aquifer under scenario 3

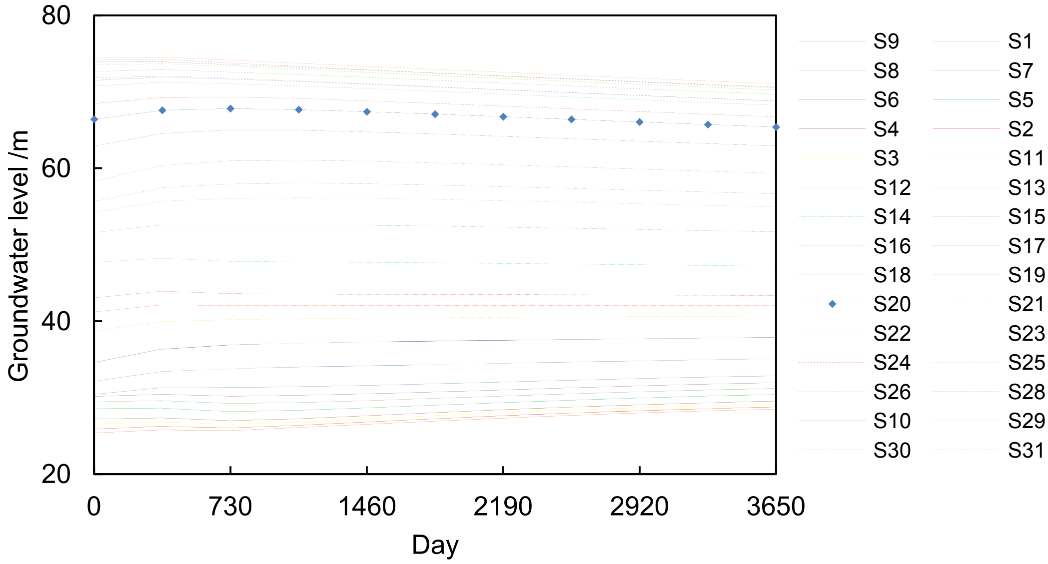

Figure 7.17 Temporal variations of groundwater level for shallow aquifer in scenario 3

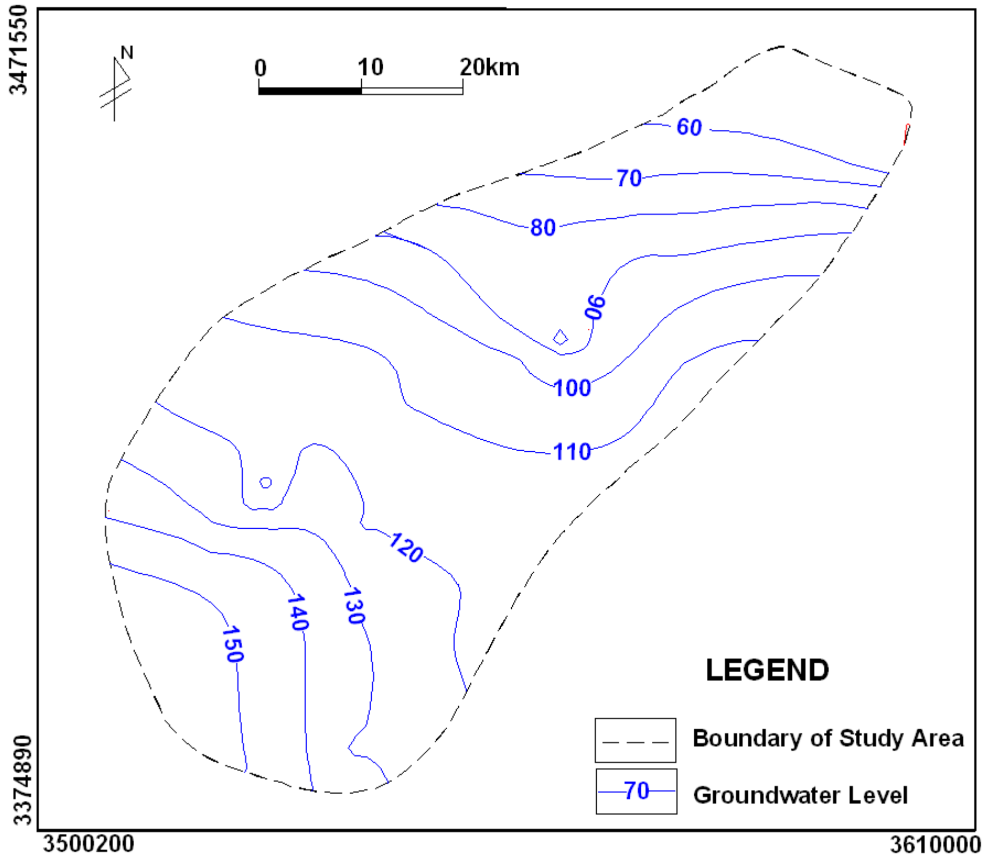

Figure 7.18 Groundwater level in 2020 for deep aquifer under scenario 3

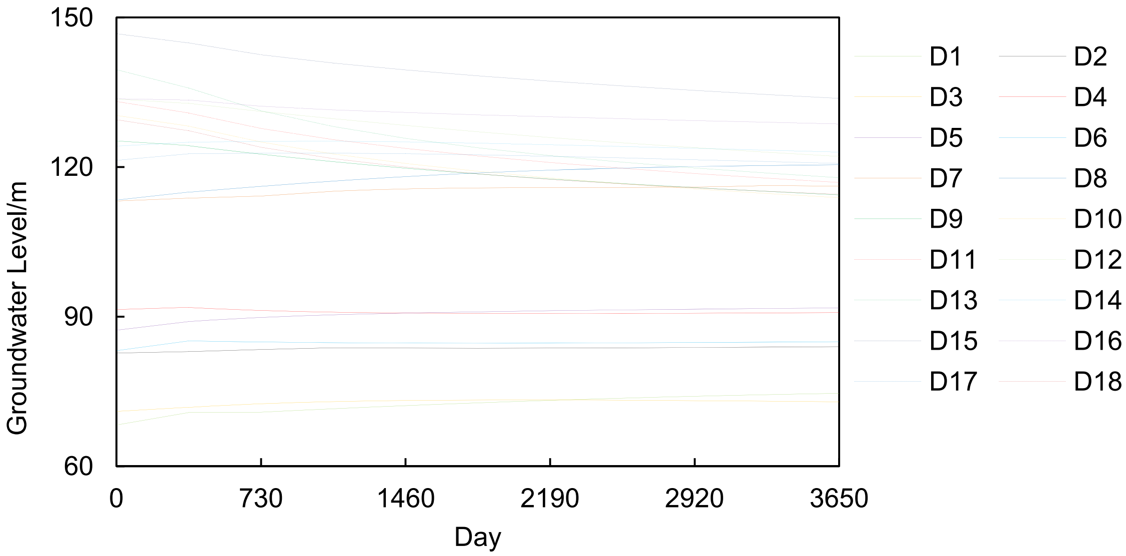

Figure 7.19 Dynamic curve of groundwater level for deep aquifer under scenario 3

7.4.3 Discussions

By compare the three exploitation scenarios, we could draw the conclusion that groundwater withdraw is the most important reason for the water table decline. The water table will decrease as long as the pumping rate is greater than the safe yield. Therefore, scenario 3 is proved to be the most suitable one in the study area.

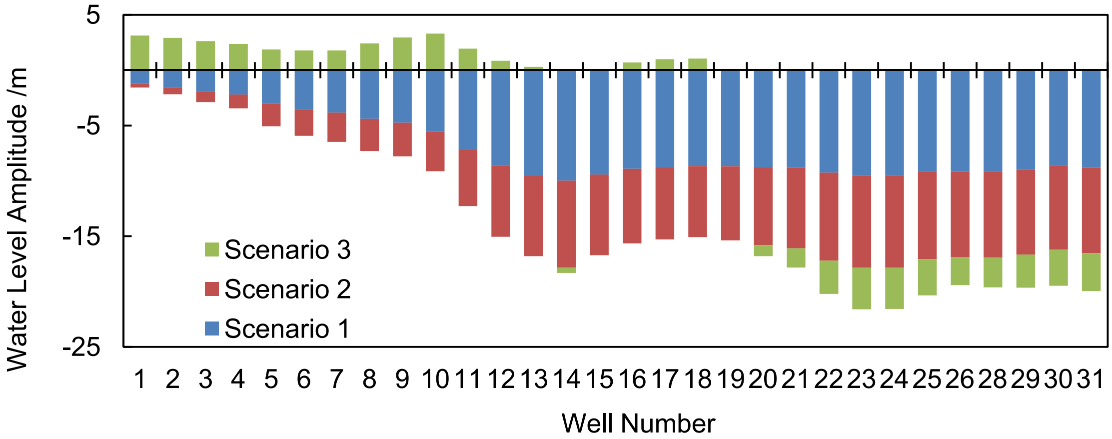

Figure 7.20 Comparison of groundwater level in shallow aquifer under three scenarios

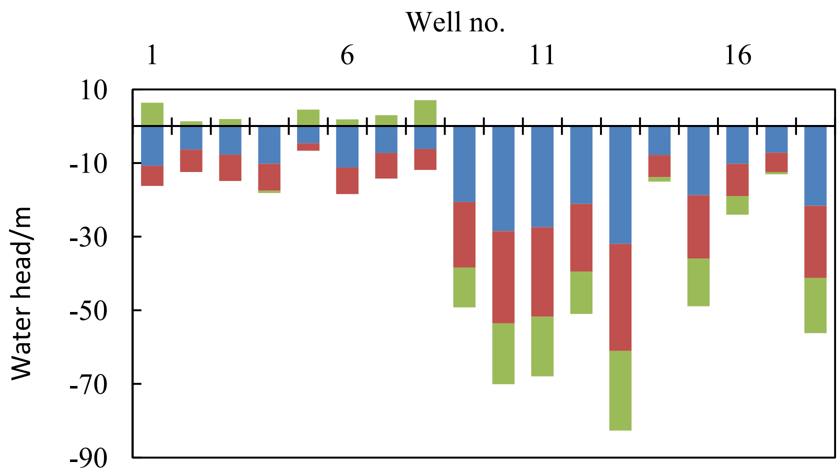

Figure 7.21 Comparison of groundwater level in deeper aquifer in three scenarios

The decline of groundwater level may result in the extension of seawater intrusion or mat change the spatial pattern of the fresh-saline interfaces. Therefore, it is vital to analyze the seawater invasion and the interface between sea water and fresh water under different scenarios.

It is manifest from Figure 7.22 ~ Figure 7.23 that elevation of interface increases with the rising pumping rate. The more amount water is exploited, the higher interface elevation will be. More precisely, the interface elevation reaches the maximum in the scenario 2 and bottoms out in scenario 3. Till 2020, the value will below the bottom elevation of shallow aquifer in which fresh water will not be affected by the seawater any longer. While deeper aquifer wells of No.1 to No.6 are still exploiting groundwater that below the interface, consequently, water resource in those wells will be still affected by modern seawater and the degradation of water quality may become more serious in scenario 1 and 2.

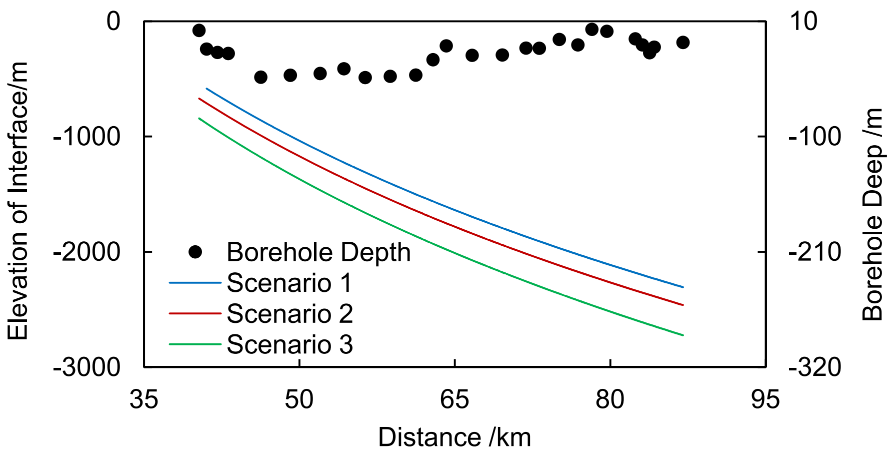

Figure 7.22 Interface elevation distribution of shallow aquifer in 2020

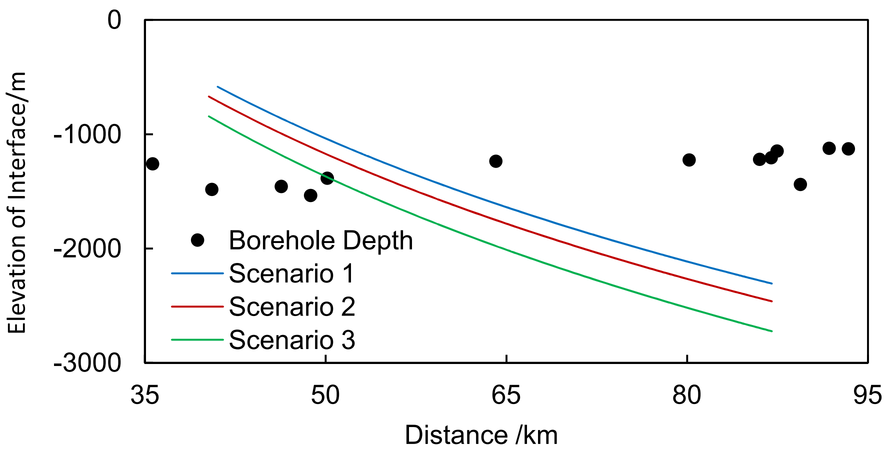

Figure 7.23 Interface elevation distribution of deeper aquifer in 2020

To sum up, we could draw the conclusion that intensive exploitation can still induce the decline of groundwater level in wells even though the total amount is equal to the safe yield. Thus, adjustment of pumping well location should be carried out in order to lessen the pumping intensity. However, the topography conditions in Wadi Bay make the adjustment difficult. In this case, intermittent exploitation measures are suggested to be adopted to control the pumping rate and the adjustment strategy is described in Table 7.13 and Figure 7.24. Besides, water quality demand in different regions for various purposes is also an issue when scenarios are proposed. Thus, it is highly recommended that further investigation should focus on regional demands to both the quality and quantity of groundwater.

Table 7.13 Pumping rate in each Well after Adjustment

Wells	Exploitation amount	Wells	Exploitation amount
1	2022	16	1500
2	1999	17	1714
3	1745	18	2057
4	1700	19	1523
5	1602	20	1074
6	1373	21	748
7	1366	22	410
8	1636	23	197
9	1915	24	217
10	1961	25	336
11	1561	26	562
12	1072	28	510
13	560	29	409
14	469	30	297
15	902	31	263

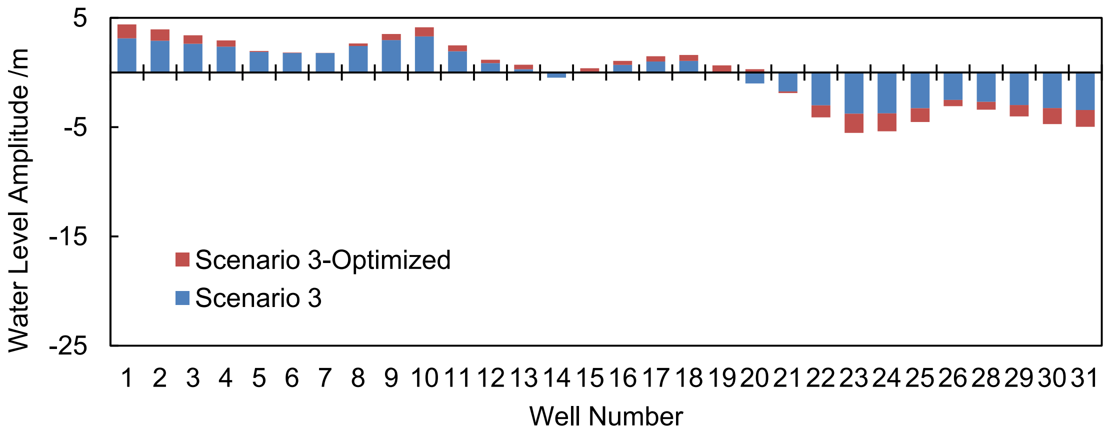

Figure 7.24 Comparison of groundwater level changes before and after optimization

7.5 Summary

The water quantity of study area was calculated based on the calibrated model. Firstly, precipitation infiltration was determined on the Pearson III crave, and three values at assurance rates of 25%, 50% and 75% were input to the model for simulations. Modelling results shows the average total recharge is 1.67×105 m^3/d, and the average pumping rates of shallow and deeper aquifer are 3.37×10^4 m^3/d and 3.56×10^4 m^3/d respectively. Furthermore, three scenarios of various withdrawals were proposed to study the response of the hydrologic system. It can be inferred from the scenario analysis that pumping rate is the major cause of the water table declines. The water table decreases as long as the pumping rate is greater than the safe yield. Therefore, an optimized strategy based on scenario 3 was put forward, and intermittent exploitation scheme is highly recommended for sustainable utilization of groundwater in this area.

Chapter 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Groundwater takes the lion's share in water supply of Wadi Baye as industries, irrigations and people rely on groundwater sources for their water demands. Therefore, the potential of this precious resource should be properly assessed and managed through different hydrogeological investigation methods.

Geology and hydrogeology of the Wadi Bayes have been characterised based on limited previous information and much current collected data. A hydrogeological conceptual model of the groundwater system was established. Hydrogeochemistry and isotope hydrology were also employed to characterise the hydrochemical processes for water origin and evolution in groundwater systems. The observed water quality changes (e.g. TDS and ions) from southern to northern part of the area with a remarkable rise at around 70 km and 55 km off the coast for shallow groundwater and deep groundwater respectively. These indicate mixing process with ancient salt water in shallow groundwater, whilst modern seawater intrusion more likely is induced in deep water apart from mixing with saline or brackish water in paleo-processes as indicated from isotopic and geochemical evolution. Artificial abstraction has also induced mixing of modern water and local old saline groundwater.

A numerical simulation of groundwater flow was conducted using Visual MODFLOW, which was calibrated using groundwater data in February 2010. The modelling results showed that the total recharge and discharge were 6.67×10^4 m^3/d

and 8.44×10^4 m^3/d respectively with the difference of about 1.77×10^4 m^3/d. This indicates a negative balance condition in aquifer development. The modelling results showed that both the shallow and deep aquifers were under negative balance The groundwater model turned out to be more sensitive to hydraulic conductivity, but the degree is different between the two aquifers and deep aquifer more sensitive to change of hydraulic conductivity.

The simulations from the well calibrated model show the average total recharge is 1.67×10^5 m^3/d, and the average pumping rates of shallow and deeper aquifer are 3.37×10^4 m^3/d and 3.56×10^4 m^3/d respectively. Further analysis of the potential of exploitation indicates overexploitation of the shallow and deep aquifers indicated a quite serious over abstraction problem.

Three scenarios of various withdrawals were proposed to predict the response of the hydrologic system. Results show that groundwater level in either aquifers will continuously decrease under Scenario 1 (increasing pumping rates by 2%) and Scenario 2 (maintaining the current pumping rate). Depression cone in deep aquifer will expand gradually, and a new cone will occur in the southern area in 2020. If the pumping rate reduces to the value of safe yield, regional groundwater level will remain constant according to the modelling results of Scenario 3, but a slight drawdown still happens around the concentrated pumping area at the end of the forecast period, year 2020.

An optimized strategy of groundwater exploitation was proposed at last for a sustainable water management. Total pumping rate should be allocated more evenly among the existing pumping wells in order to alleviate the pumping intensity of a single well. Intermittent exploitation is suggested to be adopted in this area due its complex topography.

8.2 Recommendations

Based on the overall numerical simulation of Wadi Bayes, the following recommendations were put forwards for future further study:

1) The spatial distributions of the hydro-chemical characterizations were analyzed detailed but temporal dynamics were not conducted due to insufficient data. Therefore long term monitoring system of ground water quality should be established for the whole region in order to understand the temporal hydrochemical evolutions.

2) Sufficient groundwater level monitoring wells should be placed all over the whole region or even at a larger scope in order to understand the general fluctuations in ground water levels for general regional water management. This helps to carry out transient groundwater flow modelling, so that system response can be predicted with greater confidence.

3) Conclusions about seawater intrusion will be much more reliable if a comprehensive isotopic analysis should be carried out with support of other trace elements such as Br and I to be introduced as markers for the seawater intrusion.

4) Some preliminary work was done for water supply safety and risk assessment from radioactive (α, γ) but more testing for Radon (Rn) and seismicity may be undertaken in the future.

5) Groundwater contamination from organics and heavy metals is not my scope in this study but this is an important area for future work in this part of Libya

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APPENDICES

Appendix 1 Data of Groundwater level

1) Shallow groundwater

Well No.	Location X (m)	Location Y (m)	Date	GW elevation from Sea Level(m)
1	31.02088	15.41003	2009-2-24	28
2	31.02203	15.41135	2009-2-24	28
3	31.02307	15.41254	2009-2-24	31
4	31.02387	15.41342	2009-2-24	33
5	31.02464	15.41428	2009-2-24	27
6	31.0254	15.41515	2009-2-24	30
7	31.02543	15.41152	2009-2-24	32
8	31.01004	15.3723	2009-2-24	36
9	31.00322	15.36275	2009-2-24	32
10	30.59426	15.35274	2009-2-24	36
11	30.59804	15.3451	2009-2-24	35
12	30.59047	15.33389	2009-2-24	48
13	30.58229	15.3207	2009-2-24	56
14	30.57358	15.32122	2009-2-24	50
15	30.57143	15.30003	2009-2-24	49
16	30.57043	15.28507	2009-2-25	55
17	30.55593	15.27393	2009-2-25	58
18	30.54425	15.26208	2009-2-25	62
19	30.54372	15.25514	2009-2-25	59
20	30.54182	15.24349	2009-2-25	74
21	30.52453	15.22456	2009-2-25	69
22	30.52403	15.2108	2009-2-25	73
23	30.52384	15.20039	2009-2-25	76
24	30.51505	15.19107	2006-2-26	74

Well No.	Location X (m)	Location Y (m)	Date	GW elevation from Sea Level(m)
25	30.51471	15.18344	2009-2-26	74
26	30.48518	15.19457	2009-2-26	72
28	30.48489	15.21286	2009-2-26	72
29	30.4756	15.20486	2009-2-26	74
30	30.46351	15.21178	2009-2-26	75
31	30.45411	15.2159	2009-2-26	71
1	31.02088	15.41003	2010-11-6	27.01
2	31.02203	15.41135	2010-11-6	27.11
3	31.02307	15.41254	2010-11-6	31.1
4	31.02387	15.41342	2010-11-6	33.09
5	31.02464	15.41428	2010-11-6	26.93
6	31.0254	15.41515	2010-11-6	28.99
7	31.02543	15.41152	2010-11-7	31.98
8	31.01004	15.3723	2010-11-7	35.99
9	31.00322	15.36275	2010-11-7	31.13
10	30.59426	15.35274	2010-11-7	35.15
11	30.59804	15.3451	2010-11-7	34.92
12	30.59047	15.33389	2010-11-7	47.93
13	30.58229	15.3207	2010-11-7	55.38
14	30.57358	15.32122	2010-11-7	50.45
15	30.57143	15.30003	2010-11-7	48.91
16	30.57043	15.28507	2010-11-7	54.38
17	30.55593	15.27393	2010-11-7	57.37
18	30.54425	15.26208	2010-11-7	61.99
19	30.54372	15.25514	2010-11-7	58.3

Well No.	Location X (m)	Location Y (m)	Date	GW elevation from Sea Level(m)
20	30.54182	15.24349	2010-11-8	73.39
21	30.52453	15.22456	2010-11-8	67.11
22	30.52403	15.2108	2010-11-8	72
23	30.52384	15.20039	2010-11-8	75.98
24	30.51505	15.19107	2010-11-8	73.45
25	30.51471	15.18344	2010-11-8	73.9
26	30.48518	15.19457	2010-11-8	71.62
28	30.48489	15.21286	2010-11-8	67.03
29	30.4756	15.20486	2010-11-8	71.77
30	30.46351	15.21178	2010-11-8	72.66
31	30.45411	15.2159	2010-11-8	70.99

2) Deep groundwater

Well No.	Location X (m)	Location Y (m)	Date	GW elevation from Sea Level (m)
W 01-109	15.42 52 80	31.02 34 60	2009-2-24	65.35
W 02-103	15.41 04 40	31.14 22 90	2009-2-24	87.22
W 03-102	15.39 20 60	31.14 27 70	2009-2-24	65.12
W 04-104	15.51 14 90	31.01 17 40	2009-2-24	109.5
W 5-117	15.44 47 90	30.56 50 90	2009-2-24	90.35
W 6-113	15.47 21 30	31.02 15 90	2009-2-24	87.2
W 07-139	15.27 13 30	30.35 18 30	2009-2-24	118
W 08-140	15.26 03 60	30.51 17 90	2009-2-24	109.67
W 09-150	15.18 50 00	30.50 25 80	2009-2-24	125.5
W 10-165	15.17 00 00	30.49 48 00	2009-2-26	122.24
W 11-153	15.14 54 50	30.49 44 10	2009-2-24	146.1
W 12-152	15.25 28 30	30.36 04 60	2009-2-24	125.14

Well No.	Location X (m)	Location Y (m)	Date	GW elevation from Sea Level (m)
W 13-159	15.18 41 00	30.48 52 00	2009-2-25	153.24
W 14-160	15.11 44 00	30.48 26 00	2009-2-25	122.62
W 15-161	15.11 11 00	30.47 00 00	2009-2-25	155.15
W 16-162	15.23 36 00	30.35 33 00	2009-2-25	137.9
W 17-163	15.25 00 00	30.35 00 00	2009-2-25	121.32
W 18-164	15.51 50	30.85 50 00	2009-2-26	135.7
W 01-109	15.42 52 80	31.02 34 60	2010-11-10	64.25
W 02-103	15.41 04 40	31.14 22 90	2010-11-10	86.22
W 03-102	15.39 20 60	31.14 27 70	2010-11-10	64.11
W 04-104	15.51 14 90	31.01 17 40	2010-11-10	108.3
W 5-117	15.44 47 90	30.56 50 90	2010-11-10	89.37
W 6-113	15.47 21 30	31.02 15 90	2010-11-10	86.13
W 07-139	15.27 13 30	30.35 18 30	2010-11-10	117.1
W 08-140	15.26 03 60	30.51 17 90	2010-11-10	108.65
W 09-150	15.18 50 00	30.50 25 80	2010-11-10	124.3
W 10-165	15.17 00 00	30.49 48 00	2010-11-11	121
W 11-153	15.14 54 50	30.49 44 10	2010-11-11	145.1
W 12-152	15.25 28 30	30.36 04 60	2010-11-11	124.1
W 13-159	15.18 41 00	30.48 52 00	2010-11-11	151.14
W 14-160	15.11 44 00	30.48 26 00	2010-11-11	121.42
W 15-161	15.11 11 00	30.47 00 00	2010-11-11	153.9
W 16-162	15.23 36 00	30.35 33 00	2010-11-11	133.95
W 17-163	15.25 00 00	30.35 00 00	2010-11-11	120.32
W 18-164	15.51 50	30.85 50 00	2010-11-11	134.5

Appendix 2 Data of Groundwater chemistry

1) Shallow groundwater

Well No.	Location X (m)	Location Y (m)	Date	pH	EC (uS/cm)	T (°C)	Alkalinity (mg $CaCO_3$/l)	HCO_3 (mg/l)	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
2	31.02203	15.41135	2009-2-24	7.16	8764	28.4	3200	223.4	2410	670.2	65	302.8	1730	2293	0.2	0.09	2.55	0.07	6.8	0.1
4	31.02387	15.41342	2009-2-24	7.19	10672	28.4	2920	224.7	2678	660.5	62	321.5	1698	2300	0.15	0.1	2.45	0.07	6.6	0.08
3	31.02307	15.41254	2009-2-24	7.13	9700	28.6	3000.5	219.0	2506	643.3	60	320.2	1760	2214	0.02	0.08	2.32	0.05	6.4	0.1
1	31.02088	15.41003	2009-2-24	7.15	8560	29	3100.4	215.2	2830	600.1	70	321.6	1740	2332	0.03	0.08	2.57	0.08	5.2	0.11
5	31.02464	15.41428	2009-2-24	7.15	11230	28.7	3012	218.7	2890	647.1	64	322.1	1760	2320	0.03	0.1	3.01	0.02	6.1	0.07
6	31.0254	15.41515	2009-2-24	7.14	13720	30	3000.6	214.8	2970	656.2	60	326.5	1740	2392	0.02	0.1	2.9	0.04	5.8	0.08
7	31.02543	15.41152	2009-2-24	7.16	13450	29.6	3001.5	220.3	2975	640.3	61	320.1	1643	2320	0.02	0.07	2.34	0.01	5.5	0.05
8	31.01004	15.3723	2009-2-24	7.18	10032	29.8	2920	243.1	2945	654.2	60	331.7	1632	2311	0.02	0.11	2.22	0.08	5.1	0.1
9	31.00322	15.36275	2009-2-24	7.35	9823	28	2012.3	225.4	2867	611.1	63	292.9	1635	2215	0.01	0.1	2.78	0.07	4.2	0.07
10	30.59426	15.35274	2009-2-24	7.45	8420	29.9	2143	216.7	2799	613.1	60	332.0	1621	2158	0.04	0.08	2.34	0.05	4.8	0.08
11	30.59804	15.3451	2009-2-24	7.14	8503	30	1970	229.3	2704	623.1	61	214.8	1618	2089	0.03	0.07	2.68	0.02	3.7	0.09
12	30.59047	15.33389	2009-2-24	7.3	8642	30.2	1542	214.7	2654	578.6	59	254.3	1603	1934	0.02	0.08	2.45	0.07	3.1	0.08
13	30.58229	15.3207	2009-2-24	7.21	7630	28.7	1410	233.2	2654	570.2	53	300.7	1587	1898	0.04	0.09	3.02	0.09	2.11	0.05

Well No.	Location X (m)	Location Y (m)	Date	pH	EC (uS/cm)	T (°C)	Alkalinity (mg $CaCO_3$/l)	HCO_3 (mg/l)	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
14	30.57358	15.32122	2009-2-24	7.15	7420	28.2	1345	218.7	2542	569.2	55	215.4	1568	1870	0.03	0.11	3.11	0.06	2.8	0.09
15	30.57143	15.30003	2009-2-24	7.34	8030	28.8	2430	214.8	2433	558.4	62	204.3	1432	1645	0.01	0.1	2.89	0.04	2.4	0.09
16	30.57043	15.28507	2009-2-25	7.14	7920	29	1630.3	220.3	978.5	427.3	60	198.2	954	1230	0.01	0.1	2.76	0.03	3.6	0.04
17	30.55593	15.27393	2009-2-25	7.08	7610	30.2	1432.9	219.6	895.3	500.1	54	129.4	932	1056	0.01	0.06	2	0.06	3.2	0.06
18	30.54425	15.26208	2009-2-25	7.12	5740	28.6	1435.12	221.5	864	467.2	55	254.2	879	1121	0.01	0.07	1.84	0.05	2.5	0.11
19	30.54372	15.25514	2009-2-25	7.19	5781	28	1320.25	243.4	823.4	485.2	57.2	175.3	743	934	0.02	0.1	1.76	0.04	2.7	0.05
20	30.54182	15.24349	2009-2-25	7.22	5532	27.9	1321.11	232.4	845.2	412.3	67.11	176.3	654	984	0.02	0.1	1.56	0.03	1.9	0.03
21	30.52453	15.22456	2009-2-25	7.29	5420	29	1326.3	242.8	832.8	389.3	70	132.2	702	923	0.03	0.11	2.07	0.03	1.75	0.06
22	30.52403	15.2108	2009-2-25	7.31	4687	28.8	1290.23	217.9	875.2	330.2	68	125.2	654	986	0.01	0.1	2.33	0.04	3.3	0.09
23	30.52384	15.20039	2009-2-25	7.23	4320	29	1345.24	247.8	823.7	342.1	72	134.4	634	1042	0.02	0.09	2.12	0.02	4.8	0.08
24	30.51505	15.19107	2006-2-26	7.15	4510	30	1312.27	236.1	934.6	405.2	71	119.3	511	954	0.03	0.08	1.89	0.06	6.4	0.08
25	30.51471	15.18344	2009-2-26	7.22	4820	30.1	1310.3	298.2	897.3	342.2	70	121.9	553.2	974	0.02	0.07	2.13	0.04	8.7	0.09
26	30.48518	15.19457	2009-2-26	7.21	5724	30	1314.32	331.7	906.4	329.7	69	124.3	521.3	1113	0.01	0.08	2.67	0.03	8.4	0.1
28	30.48489	15.21286	2009-2-26	7.24	5287	28.5	1320.26	332.0	921.2	328.1	70	120.1	567.5	1021	0.03	0.09	3.11	0.06	10.7	0.07
29	30.4756	15.20486	2009-2-26	7.05	5100	28	1300.26	332.0	875.9	320.1	67.5	120.1	535	999.3	0.02	0.1	3.05	0.05	1.58	0.05
30	30.46351	15.21178	2009-2-26	7.69	5048	28.6	1320.26	292.9	875.9	320.1	70	124.9	512.5	1004	0.01	0.1	2.67	0.06	2.11	0.06

Well No.	Location X (m)	Location Y (m)	Date	pH	EC (uS/cm)	T (°C)	Alkalinity (mg $CaCO_3$/l)	HCO_3 (mg/l)	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
31	30.45411	15.2159	2009-2-26	7.42	5026	28	1320.26	332.0	855.8	336.1	70	115.25	507.5	991.9	0.02	0.1	2.79	0.09	1.98	0.07
2	31.02203	15.41135	2010-11-6	7.17	8766	28.8	3220	225.3	2411.0	670.9	65.00	305.2	1733	2293	0.20	0.10	2.58	0.07	6.82	0.12
4	31.02387	15.41342	2010-11-6	7.19	10673	28.3	2921	224.8	2689	664.5	62.7	322.6	1701	2302	0.15	0.14	2.55	0.07	6.67	0.10
3	31.02307	15.41254	2010-11-6	7.14	9702	28.6	3002.5	219.11	2515	651.2	61	322.7	1766	2218	0.02	0.08	2.39	0.06	6.40	0.10
1	31.02088	15.41003	2010-11-6	7.14	8561	18.9	3191	217.3	2830	603.4	70.00	322.7	1751	2333	0.04	0.08	2.62	0.08	5.31	0.15
5	31.02464	15.41428	2010-11-6	7.16	11232	29.0	3014	218.8	2901	651.6	66	324.3	1769	2322	0.04	0.11	3.12	0.04	6.20	0.10
6	31.0254	15.41515	2010-11-6	7.15	13722	19.8	3000	215.2	2975	656.2	62.2	326.8	1745	2392	0.03	0.12	2.90	0.05	5.87	0.11
7	31.02543	15.41152	2010-11-7	7.14	13450	29.7	3002	221	2975	645.3	61	321.1	1651	2321	0.03	0.08	2.41	0.04	5.58	0.09
8	31.01004	15.3723	2010-11-7	7.18	10033	30.0	2981	245.2	2960	656.9	62	332.1	1639	2313	0.03	0.12	2.31	0.08	5.17	0.10
9	31.00322	15.36275	2010-11-7	7,30	9822	28.2	2015.4	227.7	2877	620.1	62	293.8	1645	2218	0.03	0.11	2.81	0.07	4.28	0.08
10	30.59426	15.35274	2010-11-7	7.44	8421	30.0	2201	218.6	2801	614.0	59	332.0	1624	2158	0.05	0.08	2.36	0.07	4.80	0.11
11	30.59804	15.3451	2010-11-7	7.15	8505	30.0	1972	228.9	2706	624.1	62	215.1	1621	2088	0.05	0.07	2.72	0.03	3.75	0.10
12	30.59047	15.33389	2010-11-7	7.28	8641	30.1	1550	216.1	2656	581.3	60	256.7	1603	1935	0.03	0.085	2.65	0.075	3.3	0.11
13	30.58229	15.3207	2010-11-7	7.16	7632	28.8	1432	220.7	2656	577.2	55	302.8	1589	1899	0.03	0.098	3.08	0.091	2.19	0.049
14	30.57358	15.32122	2010-11-7	7.17	7420	28.8	1347	218.7	2550	571.6	57	217.7	1571	1872	0.034	0.113	3.19	0.07	2.87	0.099
15	30.57143	15.30003	2010-11-7	7.33	8032	28.3	2431.5	214.8	2434	561.4	63	210.3	1435	1644	0.02	0.15	2.97	0.048	2.44	0.097

Well No.	Location X (m)	Location Y (m)	Date	pH	EC (uS/cm)	T (°C)	Alkalinity (mg $CaCO_3$/l)	HCO_3	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
								(mg/l)												
16	30.57043	15.28507	2010-11-7	7.16	7921	28.6	1632.2	222.2	979.0	429.8	62	198.9	958	1233	0.02	0.16	2.78	0.06	3.69	0.063
17	30.55593	15.27393	2010-11-7	7.09	7612	30.0	1433.7	219.9	901.4	512.2	56	131.3	936	1057	0.013	0.069	2.12	0.06	3.22	0.095
18	30.54425	15.26208	2010-11-7	7.13	5741	28.7	1434.2	222.3	866.3	469.7	58	256.9	881	1124	0.014	0.078	1.91	0.08	2.52	0.13
19	30.54372	15.25514	2010-11-7	7.20	5780	28.2	1323	244.4	825.4	485.9	58	177.4	743	938	0.029	0.12	1.85	0.04	2.71	0.057
20	30.54182	15.24349	2010-11-8	7.22	5533	27.6	1325.2	234.2	860.1	419.7	67.8	179.2	657	984	0.023	0.14	1.58	0.05	2.1	0.039
21	30.52453	15.22456	2010-11-8	7.27	5420	29.1	1327	248.2	833.6	392.6	71	134.6	711	924	0.038	0.12	2.14	0.04	1.79	0.059
22	30.52403	15.2108	2010-11-8	7.30	4688	28.7	1291.4	219.6	879.9	338.8	70	125.8	659	988	0.019	0.1	2.37	0.08	3.31	0.098
23	30.52384	15.20039	2010-11-8	7.24	4321	30.0	1344.3	248.5	829.7	348.4	72	135.1	638	1043	0.031	0.095	2.18	0.07	4.85	0.09
24	30.51505	15.19107	2010-11-8	7.14	4512	30.0	1315.3	234.6	939.3	415.3	73	121.2	518.2	954	0.038	0.088	1.91	0.07	6.7	0.076
25	30.51471	15.18344	2010-11-8	7.22	4820	31.0	1312.4	300.2	904.3	343.0	71	122.2	558	976	0.02	0.072	2.18	0.07	8.94	0.098
26	30.48518	15.19457	2010-11-8	7.21	5723	30.0	1316.5	332.6	906.9	331.4	69.7	125.8	523.4	1115	0.019	0.087	2.69	0.07	8.76	0.10
28	30.48489	15.21286	2010-11-8	7.25	5289	28.8	1320.9	332.1	923.2	331.3	71	121.0	570.5	1021	0.037	0.1	3.19	0.06	10.98	0.08
29	30.4756	15.20486	2010-11-8	7.07	5102	28.8	1303.3	332.2	879.7	323.6	71	121.1	538	1000	0.025	0.16	3.11	0.08	1.87	0.11
30	30.46351	15.21178	2010-11-8	7.70	5051	28.3	1320	291.9	881.2	323.8	71	126.2	518.5	1006	0.021	0.12	2.7	0.04	3.1	0.10
31	30.45411	15.2159	2010-11-8	7.43	5025	28.6	1320.11	332.2	860.3	331.3	71.5	115.25	509.7	993	0.029	0.1	2.79	0.05	2.98	0.11

2) Deep groundwater

Well No.	Location X	Location Y	Sampling	pH	EC	T	Alkalinity	HCO_3	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
	(m)	(m)	Date		(uS/cm)	(°C)	(CaCO3, mg/l)	(mg/l)												
W 01-109	15°71'46.7"	31°04'29.4"	2009-2-24	7.2	2415	73	620.12	273.37	463.1	128.03	58	72.03	236	318	0.05	0.02	1.8	0.09	0.38	0.15
W 02-103	15.41 04 40	31.14 22 90	2009-2-24	7.3	2690	67	680.14	253.84	589	128.03	70	86.44	264	293	0.03	0.01	1.56	0.06	0.48	0.01
W 03-102	15.39 20 60	31.14 27 70	2009-2-24	7.01	3940	65	720.14	439.34	654.4	168.04	120	72.03	504	659	0.02	0.01	1.7	0.07	0.97	0.21
W 04-104	15.51 14 90	31.01 17 40	2009-2-24	7.03	4033	70	760.15	468.63	684.61	192.05	120	86.44	508	639.59	0.07	0.02	1.09	0.04	0.19	0.13
W 5-117	15.44 47 90	30.56 50 90	2009-2-24	7.26	2799	70	660.13	312.42	513.46	216.05	68	28.81	300	398.41	0.03	0.05	1.57	0.01	4.5	0.14
W 6-113	15.47 21 30	31.02 15 90	2009-2-24	7.05	2902	73	680.14	292.9	553.73	144.04	80	76.83	308	409.11	0.01	0.04	2.12	0.04	5.87	0.09
W 07-139	15.27 13 30	30.35 18 30	2009-2-24	7.35	2267	56	540.11	273.37	432.92	120.03	48	57.62	244	286.46	0.01	0.02	2.45	0.02	0.11	0.07
W 08-140	15.26 03 60	30.51 17 90	2009-2-24	7.25	2440	56	560.11	253.84	503.39	136.03	64	52.82	266	289.75	0.07	0.01	2,34	0.09	0.27	0.15
W 09-150	15.18 50 00	30.50 25 80	2009-2-24	7.17	2350	60	500.1	292.9	458.08	96.02	60	62.43	276	277.4	0.08	0.05	0.96	0.1	0.61	0.13
W 10-165	15.17 00 00	30.49 48 00	2009-2-26	7.15	2385	63	530	292.9	440.2	111.05	54	65.3	236	267.1	0.06	0.03	0.88	0.08	0.93	0.05
W 11-153	15.14 54 50	30.49 44 10	2009-2-24	7.1	2250	64	540.11	292.9	432.92	104.03	52	67.23	238	260.12	0.04	0.04	1.1	0.05	3	0.07
W 12-152	15.25 28 30	30.36 04 60	2009-2-24	7.32	2326	64	560.11	292.9	442.98	112.03	52	67.23	246	283.99	0.03	0.04	1.23	0.03	2.53	0.13
W 13-159	15.18 41 00	30.48 52 00	2009-2-25	7.34	2345	61	563.2	294.8	479.993	110.08	54	65	272	268.22	0.06	0.01	2.95	0.06	1.67	0.12

Well No.	Location X (m)	Location Y (m)	Sampling Date	pH	EC (uS/cm)	T (°C)	Alkalinity (CaCO3, mg/l)	HCO_3 (mg/l)	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
W 14-160	15.11 44 00	30.48 26 00	2009-2-25	7.23	2456	64	592.12	289.9	489.919	111.03	62	70	264	267.3	0.08	0.03	3.32	0.01	0.98	0.1
W 15-161	15.11 11 00	30.47 00 00	2009-2-25	7.33	2435	64	548.13	297.3	399.876	112.03	58	69	256	282	0.04	0.01	1.54	0.012	0.23	0.12
W 16-162	15.23 36 00	30.35 33 00	2009-2-25	7.3	2376	63	562.11	292.7	509.771	114.04	56	64	252	324	0.02	0.03	1.34	0.02	1.83	0.08
W 17-163	15.25 00 00	30.35 00 00	2009-2-25	7.25	2328	63	619.12	283.4	519.697	106.02	55	63.34	266	298.6	0.05	0.05	2.27	0.03	0.76	0.1
W 18-164	15.51 50	30.85 50 00	2009-2-26	7.09	2561	62	598.2	285.2	499.845	121.05	53	62.23	256	287.4	0.04	0.06	1.34	0.034	0.79	0.02
W 01-109	15°71'46.7"	31°04'29.4"	2010-11-10	7.25	2416	73	620.12	195.26	614.14	96.02	94	91.24	376	501.71	0.05	0.03	2.08	0.085	1.44	0.16
W 02-103	15.41 04 40	31.14 22 90	2010-11-10	7.31	2692	66	680.14	273.37	609.1	120.03	98	79.23	400	519.82	0.04	0.02	1.97	0.08	1.08	0.02
W 03-102	15.39 20 60	31.14 27 70	2010-11-10	7.08	3940	65	720.14	273.37	463.12	128.03	58	72.03	236	318.12	0.04	0.01	2.11	0.083	0.38	0.2
W 04-104	15.51 14 90	31.01 17 40	2010-11-10	7.03	4032	71	760.15	253.84	503.39	136.03	60	62.43	264	319.38	0.06	0.02	1.96	0.06	0.15	0.14
W 5-117	15.44 47 90	30.56 50 90	2010-11-10	7.25	2800	70	660.13	292.9	513.46	88.02	42	110.45	262	316.91	0.04	0.06	1.54	0.01	7.8	0.14
W 6-113	15.47 21 30	31.02 15 90	2010-11-10	7.04	2903	73	680.14	273.37	513.46	120.03	68	81.63	264	337.49	0.02	0.05	2	0.07	1.27	0.1
W 07-139	15.27 13 30	30.35 18 30	2010-11-10	7.36	2267	55	540.11	468.63	684.61	192.05	120	86.44	508	639.59	0.01	0.03	2.78	0.04	0.19	0.09
W 08-140	15.26 03 60	30.51 17 90	2010-11-10	7.27	2440	57	560.11	380.76	684.61	152.04	120	81.63	520	696.39	0.07	0.02	2.22	0.08	1.75	0.14
W 09-150	15.18 50 00	30.50 25 80	2010-11-10	7.19	2352	61	500.1	292.9	503.39	136.03	74	96.04	320	556.45	0.07	0.04	1.52	0.12	0.66	0.14
W 10-165	15.17 00 00	30.49 48 00	2010-11-11	7.15	2384	63	530	371	704.75	160.04	130	72.03	540	707.91	0.07	0.05	1.18	0.06	6.9	0.06

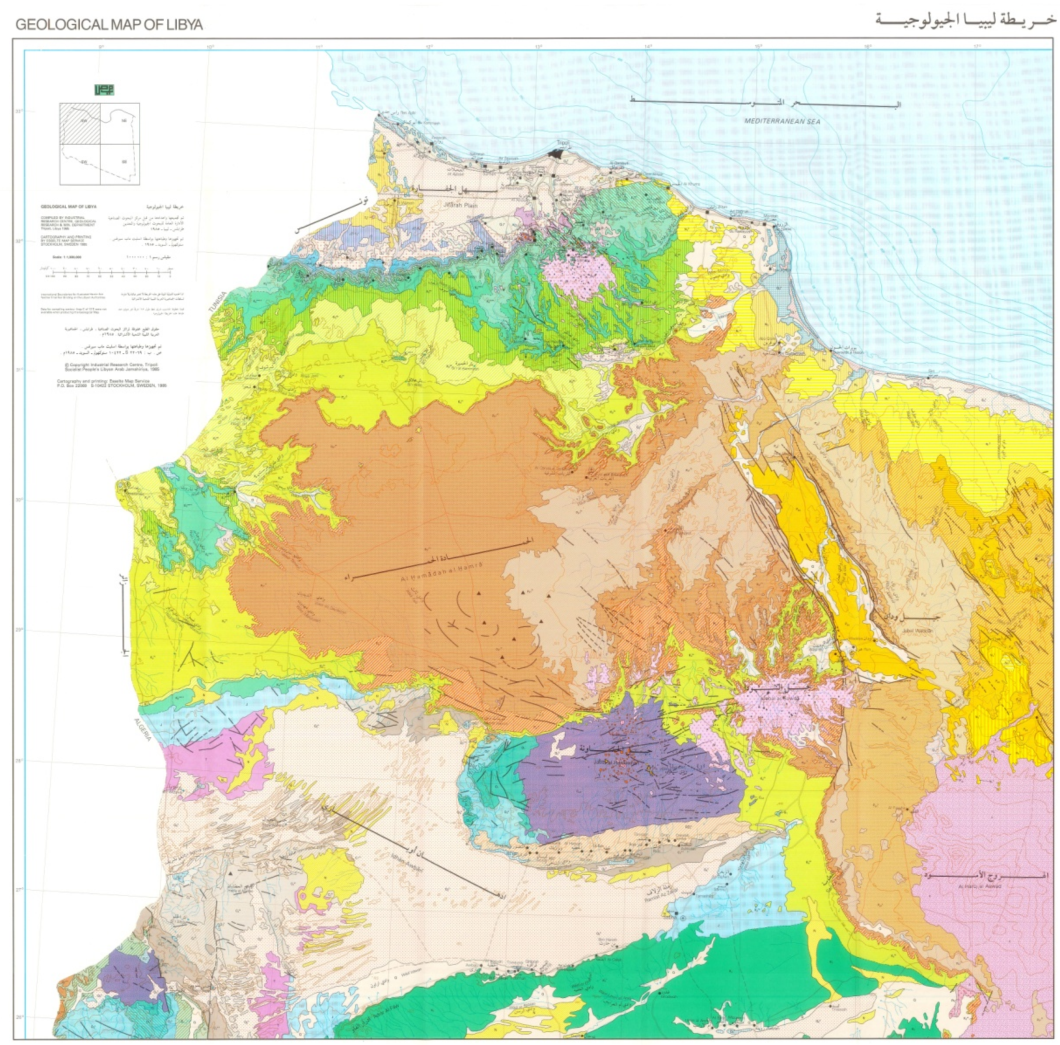
Well No.	Location X (m)	Location Y (m)	Sampling Date	pH	EC (uS/cm)	T (°C)	Alkalinity (CaCO3, mg/l)	HCO_3	Cl	Ca	K	Mg	Na	SO_4	Sr	Mn	Si	Ba	NO_3	NH_4
								(mg/l)												
W 11-153	15.14 54 50	30.49 44 10	2010-11-11	7.11	2251	64	540.11	292.9	553.73	144.04	80	76.83	308	409.11	0.05	0.05	1.78	0.054	5.87	0.07
W 12-152	15.25 28 30	30.36 04 60	2010-11-11	7.34	2328	65	560.11	283.13	538.63	144.04	70	72.03	312	418.99	0.04	0.06	1.23	0.05	0.36	0.12
W 13-159	15.18 41 00	30.48 52 00	2010-11-11	7.34	2345	61	563.2	312.42	523.53	152.04	68	72.03	304	414.46	0.06	0.02	2.82	0.08	1.67	0.12
W 14-160	15.11 44 00	30.48 26 00	2010-11-11	7.22	2457	66	592.12	351.48	533.59	160.04	74	81.63	320	372.48	0.09	0.03	3.28	0.013	0.98	0.11
W 15-161	15.11 11 00	30.47 00 00	2010-11-11	7.35	2436	65	548.13	312.42	513.46	216.05	68	28.81	300	398.41	0.06	0.02	2	0.012	1.21	0.13
W 16-162	15.23 36 00	30.35 33 00	2010-11-11	7.31	2380	63	562.11	253.84	543.66	128.03	60	81.63	240	271.85	0.03	0.04	1.45	0.034	2.04	0.09
W 17-163	15.25 00 00	30.35 00 00	2010-11-11	7.25	2326	63	619.12	292.9	513.46	144.04	64	76.83	294	418.57	0.06	0.05	2.27	0.06	0.98	0.12
W 18-164	15.51 50	30.85 50 00	2010-11-11	7.11	2563	63	598.2	253.84	523.53	128.03	72	72.03	316	433.39	0.03	0.05	1.64	0.041	1.39	0.03

Appendix 3 Isotope data of groundwater

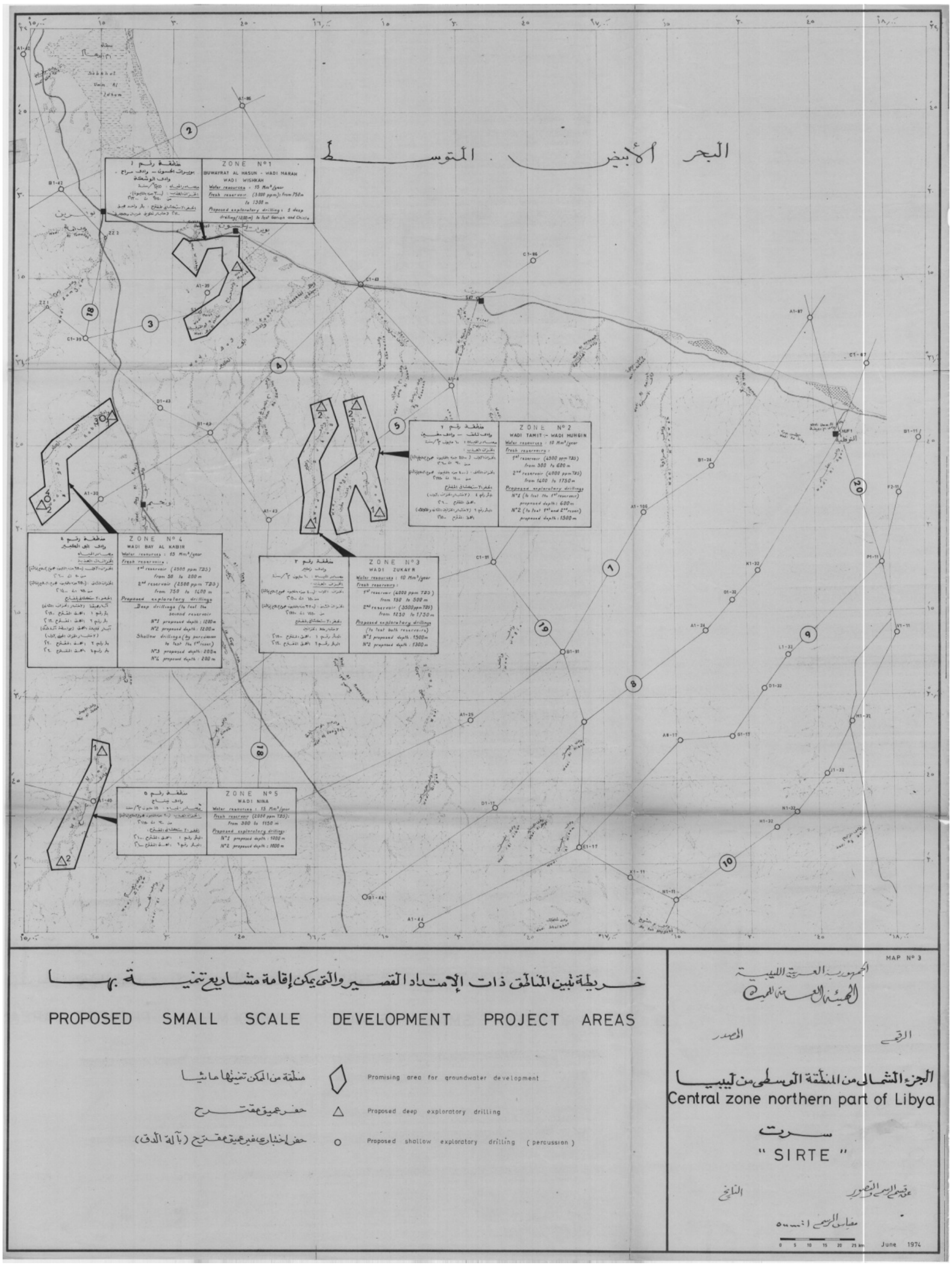
Well No.	Location X (m)	Location Y (m)	Date of supmtion	δ^{18}O (‰ vs Smow)	δ^{2}H (‰ vs Smow)
2	31.02203	15.41135	2009-11-18	-7.78	-64.59
4	31.02387	15.41342	2009-11-18	-7.77	-64.57
3	31.02307	15.41254	2009-11-18	-7.65	-59.34
1	31.02088	15.41003	2009-11-18	-7.61	-63.67
5	31.02464	15.41428	2009-11-18	-7.7	-59.58
6	31.0254	15.41515	2009-11-18	-7.59	-58.35
7	31.02543	15.41152	2009-11-18	-7.86	-65.03
8	31.01004	15.3723	2009-11-18	-7.78	-64.59
9	31.00322	15.36275	2009-11-18	-7.86	-65.03
10	30.59426	15.35274	2009-11-18	-7.58	-62.78
11	30.59804	15.3451	2009-11-18	-7.59	-62.69
12	30.59047	15.33389	2009-11-18	-7.85	-64.57
13	30.58229	15.3207	2009-11-18	-7.57	-59.40
14	30.57358	15.32122	2009-11-18	-7.60	-64.56
15	30.57143	15.30003	2009-11-18	-7.48	-63.66
16	30.57043	15.28507	2009-11-18	-7.69	-64.61
17	30.55593	15.27393	2009-11-18	-7.77	-64.57
18	30.54425	15.26208	2009-11-18	-7.65	-59.34
19	30.54372	15.25514	2009-11-18	-7.63	-59.74
20	30.54182	15.24349	2009-11-18	-7.54	-64.42
21	30.52453	15.22456	2009-11-18	-9.67	-71.23
22	30.52403	15.2108	2009-11-18	-9.34	-70.57
23	30.52384	15.20039	2009-11-18	-9.02	-71.47
24	30.51505	15.19107	2009-11-18	-9.26	-66.98
25	30.51471	15.18344	2009-11-18	-9.49	-67.79

Well No.	Location X (m)	Location Y (m)	Date of supmtion	$\delta^{18}O$ (‰ vs Smow)	$\delta^{2}H$ (‰ vs Smow)
26	30.48518	15.19457	2009-11-18	-9.49	-72.21
28	30.48489	15.21286	2009-11-18	-9.84	-72.14
29	30.4756	15.20486	2009-11-18	-9.71	-72.11
30	30.46351	15.21178	2009-11-18	-9.66	-70.36
31	30.45411	15.2159	2009-11-18	-9.93	-72.25
W 01-109	15.42 52 80	31.02 34 60	2009-11-18	-9.26	-66.99
W02-103	15.41 04 40	31.14 22 90	2009-11-18	-9.39	-64.91
W 03-102	15.39 20 60	31.14 27 70	2009-11-18	-9.17	-70.06
W 04-104	15.51 14 90	31.01 17 40	2009-11-18	-9.08	-68.72
W 5-117	15.44 47 90	30.56 50 90	2009-11-18	-8.33	-66.68
W 6-113	15.47 21 30	31.02 15 90	2009-11-18	-8.81	-69.54
W 07-139	15.27 13 30	30.35 18 30	2009-11-18	-10.00	-69.45
W 08-140	15.26 03 60	30.51 17 90	2009-11-18	-10.15	-69.74
W 09-150	15.18 50 00	30.50 25 80	2009-11-18	-10.04	-70.57
W 10-165	15.17 00 00	30.49 48 00	2009-11-18	-10.06	-70.53
W 11-153	15.14 54 50	30.49 44 10	2009-11-18	-10.01	-69.63
W 12-152	15.25 28 30	30.36 04 60	2009-11-18	-10.10	-70.25
W 13-159	15.18 41 00	30.48 52 00	2009-11-18	-10.11	-69.71
W 14-160	15.11 44 00	30.48 26 00	2009-11-18	-10.09	-69.65
W 15-161	15.11 11 00	30.47 00 00	2009-11-18	-10.07	-70.71
W 16-162	15.23 36 00	30.35 33 00	2009-11-18	-10.10	-69.55
W 17-163	15.25 00 00	30.35 00 00	2009-11-18	-10.12	-70.58
W 18-164	15.51 50	30.85 50 00	2009-11-18	-10.10	-69.78

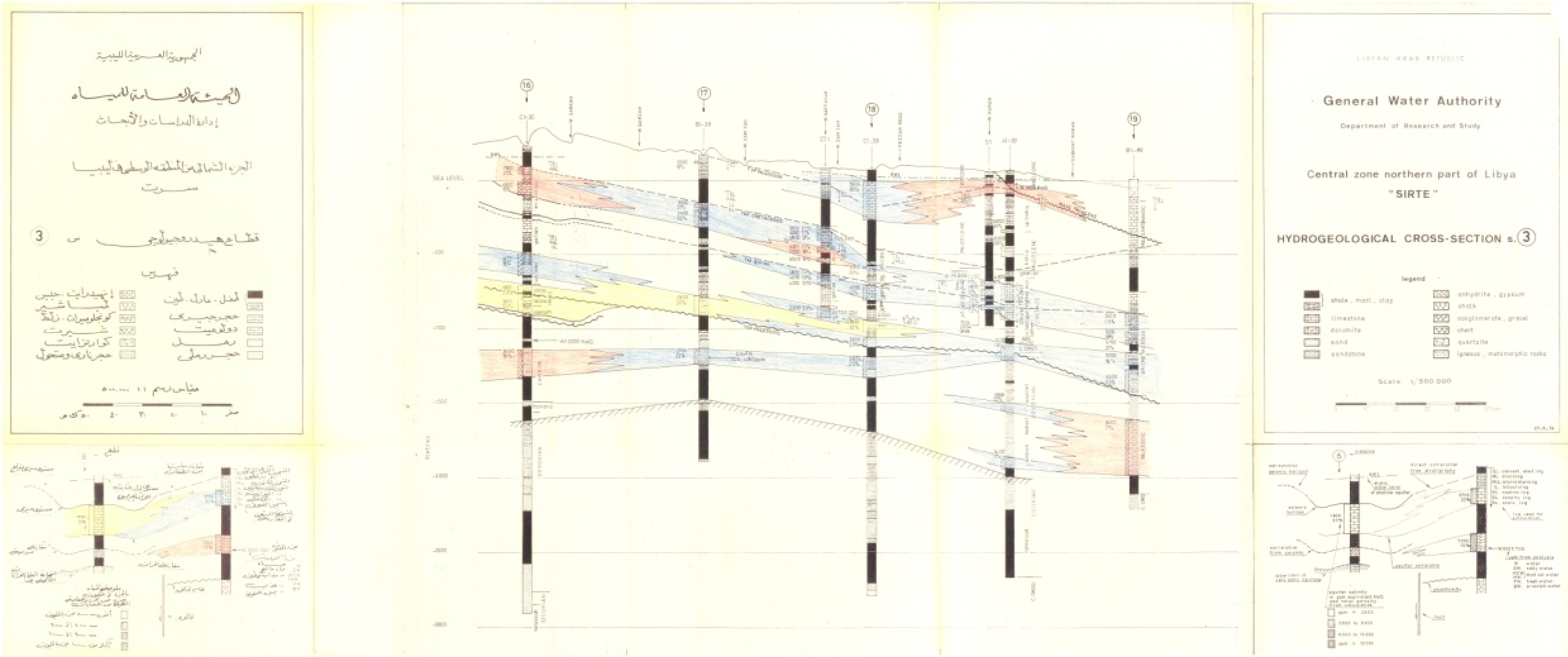
Appendix 4 Geological map and Cross sections



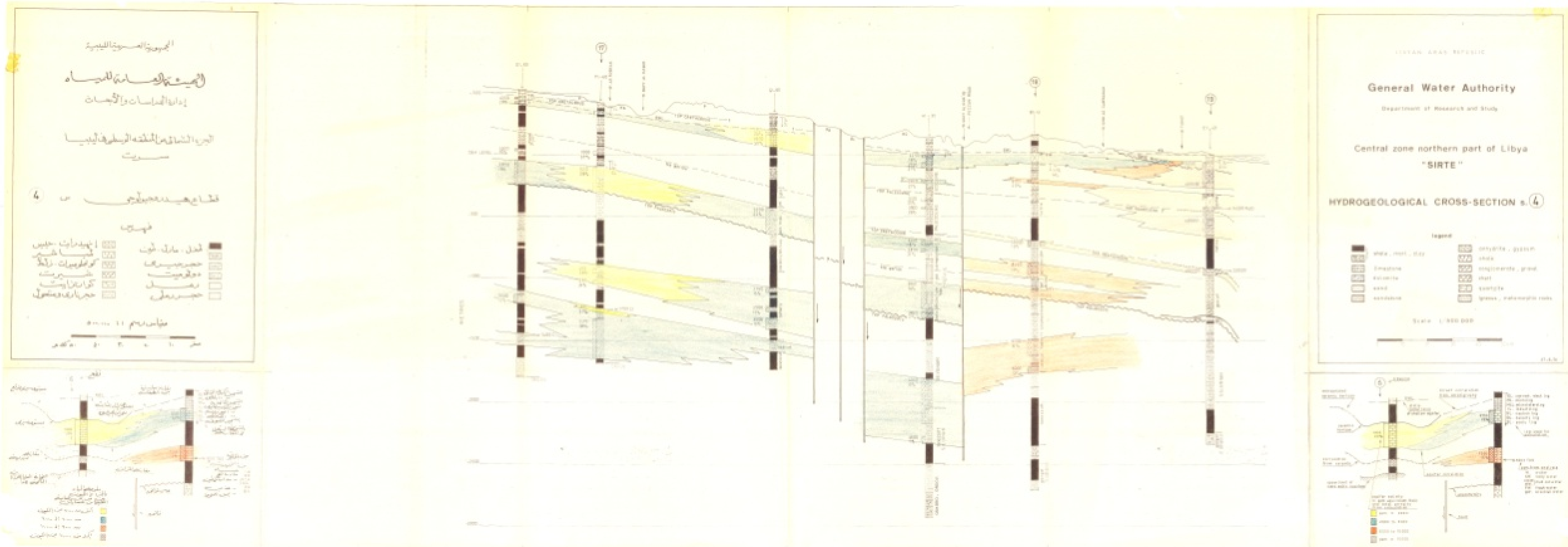
Geological map of Libya



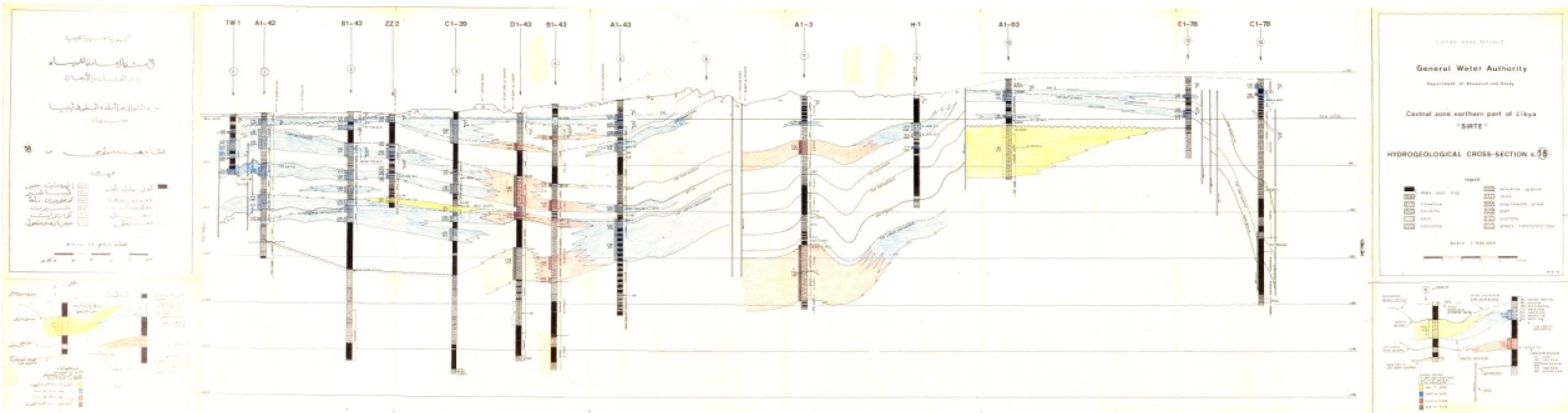
Distribution of Cross Sections



Cross Section III



Cross Section IV



Cross Section XVIII

Appendix 5 Meteorological data

Bunjeem Satation

The averge of Temprature

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	13.8	12.6	15.2	21.6	24.7	28.9	31.2	30.2	29.6	27.4	18.8	14.2
2004	12.7	15.5	18.7	21.9	24.8	28.1	28.8	30.9		25.6	16.7	13.7
2005	11.5	13.2	18.1	21.0	25.2	26.8	30.6	30.4	29.1	24.7	18.6	14.3

The Average of Relative Humidity

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	63	56	56	49	50	50	48	55	51	49	50	59
2004	70	61	69	49	48	39	60	57		58	65	69
2005	70	58	53	52	49	60	59	58	54	62	60	66

The Average of Evaporation amount

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003												
2004												
2005										8.8	7.1	6.2

The average of duration of Solar Brightness

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003					10.6	9.8	11.3	11.4	8.8	8.5	8.7	7.3
2004	7.5	7.8	7.5	8.9	8.5					9.4	7.7	7.0
2005	7.4	7.9	7.9	8.7	10.8	8.2	11.7	10.4	9.6	8.7	7.3	4.9

Total montly amount of Rainfall

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	0.0	9.7	6.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0
2004	1.0	0.0	7.5	0.0	0.0	3.2	0.0	0.0		0.0	0.0	3.0
2005	6.5	1.5	3.5	0.0	0.0	10.5	0.0	0.0	0.0	6.5	0.5	6.0

Musrata Station

Average of Temprature

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	15.2	13.4	14.8	19.0	21.4	25.6	29.2	28.5	27.7	27.3	20.5	15.5
2004	13.7	16.1	17.1	19.4	21.3	24.6	26.1	28.5	25.6	25.6	19.1	15.4
2005	12.4	13.1	16.7	19.0	22.4	24.5	28.0	27.7	27.2	24.2	19.5	15.0

Average of relative Humidity

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	68	69	76	72	76	80	74	76	74	72	70	67
2004	71	73	74	70	72	72	78	73	70	67	67	70
2005	76	65	73	70	74	74	70	73	72	76	72	80

Average of Evaporation amount

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	5.7	5.2	3.6	5.5	5.1	4.3	5.8	4.7	5.4	6.0	5.5	5.5
2004	4.9	4.8	4.5	5.6	5.8	5.9	4.2	6.1	5.6	6.8	6.1	6.0
2005	4.5	6.1	5.1	6.5	6.4	5.1	6.7	5.9	6.9	5.2	5.4	3.9

Average of duration of the solar brithness

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	6.8	6.4	8.0	9.2	10.8	11.0	12.0	11.9	8.6	7.8	7.2	6.6
2004	7.1	7.3	5.6	9.6	9.5	12.0	12.4	11.0	9.7	8.9	7.2	6.5
2005	5.4	7.6	7.3	8.9	10.9	10.5	11.9	10.7	8.9	8.7	7.1	4.5

Total Montly amount of Rainfall

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	50.6	18.6	49.2	2.4	0.0	0.0	0.0	3.3	54.6	0.2	125.7	76.2
2004	37.2	4.2	113.6	22.0	0.0	0.0	0.0	0.0	9.2	0.0	44.5	21.5
2005	64.9	9.6	20.9	1.4	0.0	0.3	0.0	0.0	1.0	14.5	12.2	76.4

Hun Station

Average of Temprature

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	13.5	12.5	14.7	21.6	25.6	29.4	30.9	30.1	29.8	27.2	19.4	13.8
2004	12.0	15.4	19.1	22.2	25.4	29.2	28.8	30.3	26.4	24.5	17.5	13.6
2005	11.3	12.9	18.9	21.6	25.3	27.8	30.6	30.7	29.2	24.6	18.2	14.4

Average relative of Humidty

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	49	53	50	42	36	37	41	44	42	37	48	48
2004	51	49	45	37	36	33	38	38	48	40	47	57
2005	54	48	37	33	29	41	33	35	40	48	49	53

The Average Amount of Evaporation

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	7.2	7.0	7.8	12.1	13.8	14.1	15.0	12.1	13.8	12.0	8.3	7.4
2004	6.1	8.3	9.8	13.0	14.6	16.1	14.5	14.5	10.5	10.9	8.2	6.1
2005	5.9	7.8	11.7	15.5	15.8	14.1	17.0	15.6	14.5	10.0	7.8	6.9

Average duration of the solar brightness

العنصر : متوسط مدة سطوع الشمس

YEAR	JAN.	FEB.	MAR	APR	MAY	JUN	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000	7.5	8.6	10.4	9.3	10.2	12.8	12.7	12.2	10.4	8.9	9.3	8.2
2001	9.5	9.2	9.8	9.6	10.8	12.6	12.4	11.9	10.0	9.7	8.5	8.3
2002	7.9	8.9	8.6	9.2	10.2	12.6	11.5	11.0	9.0	9.1	8.8	8.3
2003	7.7	8.9	9.1	9.4	11.7	11.9	12.6	12.0	10.2	9.6	8.4	8.3
2004	8.2	8.0	8.0	10.5	8.9	11.8	12.9	12.0	10.1	9.9	7.9	6.5
2005	7.1	7.3	8.1	9.6	11.7	11.0	12.6	11.8	9.9	8.9	8.1	7.1

Total montly rainfall

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	1.8	15.8	0.6	20.5	0.0	0.4	0.0	0.0	0.0	0.8	0.0	0.0
2004	0.8	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.3
2005	0.2	7.4	0.4	0.0	0.3	19.1	0.0	0.0	0.0	1.3	0.0	0.0

Sirt Station

Average amount of Temprature

YEAR	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	14.9	12.9	15.1	18.8	20.9	25.1	28.5	28.7	28.0	27.3	20.7	15.3
2004	13.5	15.8	17.4	20.3	21.7	24.7	25.6	27.7	25.6	26.0	19.7	15.7
2005	13.3	14.2	17.3	19.6	22.3	23.7	27.6	27.5	27.2	24.2	19.7	16.1

The Average of Relative Humidity

YEAR	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	70	70	82	75	79	80	75	74	71	67	66	66
2004	66	66	77	63	76	74	83	76	77	62	61	67
2005	72	67	74	67	72	81	78	78	74	73	70	69

The Average amount of Evaporation

YEAR	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	5.8	6.4	5.3	6.3	4.6	5.5	6.4	6.5	7.6	9.2	8.5	5.2
2004	6.6	6.6	6.3	9.9	6.8	7.5	5.1	6.5	6.8	10.6	8.6	8.4
2005	6.1	8.2	6.9	10.4	8.8	4.8	7.4	6.5	6.3	5.8	5.2	5.1

The Average of duration of solar brithness

YEAR	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	6.9	7.4	8.2	9.5	10.4	11.0	12.1	11.8	9.7	8.5	8.3	6.2
2004	6.4	7.4	6.3	8.7	7.8	11.7	12.2	11.4	10.3	9.2	7.3	5.9
2005	5.1	7.6	7.1	8.8	11.3	9.6	12.1	11.5	9.3	8.4	7.6	5.6

Total montly amount of Rainfall

YEAR	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
2000												
2001												
2002												
2003	30.8	34.6	52.1	18.5	0.0	0.7	0.0	0.0	11.5	0.4	1.7	55.1
2004	32.0	9.0	26.2	0.0	4.0	0.2	0.0	0.0	2.1	0.0	9.0	20.6
2005	87.1	19.2	11.4	0.0	0.0	8.2	0.0	0.0	4.0	6.0	12.4	44.9